AN INTEGRATED RAPID HYDROGEOLOGIC APPROACH TO DELINEATE AREAS AFFECTED BY ADVECTIVE TRANSPORT IN MANTLED KARST, WITH AN APPLICATION TO CLEAR CREEK BASIN, WASHINGTON COUNTY, ARKANSAS

A dissertation submitted in partial fulfillment
of the requirements for the degree of
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By

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INTRODUCTION

Predictive transport modeling in karst has been considered by many well-respected researchers as unlikely; however, it is also looked upon as one of the most essential and challenging topics in groundwater modeling. This study addressed that challenge and successfully produced a model that predicts possible advective transport routes in a fractured, mantled karst environment.

The primary intent of this dissertation is to develop a model to predict possible advective transport routes in mantled karst. Development includes theoretical, empirical, and practical testing of the model in and near Clear Creek Basin, Washington County, Arkansas. Because similar physiographic settings are common elsewhere in the midcontinent of the United States (Brahana 2000), it is also the intent of this study to provide a method of predicting the advective transport routes in other areas where lineament data have been defined in a mantled karst. The method developed to predict advective transport is simple and easily applied to other fractured karst areas. The model's simplicity was achieved by utilizing the most meaningful data that are universally available, or can be obtained rapidly by remote sensing.

The model was developed using ArcView 3.2 Geographical Information System (GIS) software which can be applied to areas of similar hydrogeology. The model may be beneficial and economical to citizens, regulators, and researchers because it can be used to predict routes of travel with little data. However, the model should be used only by persons versed in karst hydrology because of the complexity and uniqueness that karst hydrogeology encompasses.

The study area selected to test the model developed in this research was the area in and near Clear Creek Basin, Washington County, Arkansas. A vast amount of data has been collected over many years in and near Clear Creek Basin. The data sources include masters theses, government reports, newspaper articles, and personal interviews. The data also include a major spill from a tanker truck in 1971, which provided flow path verification of the model and confirmed the model's use for an actual case study.

The model requires only two data sets, 1) a Digital Elevation Models (DEM), and 2) digitized lineament data for the location being studied. The model is designed to predict the flow from a point location; this point can be considered a spill point for simplicity. The model does not consider the effects of soil, epikarst, bedding planes, water table or confining layers in determining the routes of travel. The exclusion of these data will be discussed in the literature review and methods chapters.

OBJECTIVE

The main objectives of this study are 1) to integrate an understanding of flow and transport in mantled karst settings and 2) to develop a simple model that would predict possible advective routes of travel in a mantled karst in an economical, timely manner. The scope was narrowed to exclude time-of-travel, diffusion, dispersion, and sorption.

The scope of this project is focused. First, it deals only with advective transport. It does not consider concentration variations -- nor does it consider temporal or transient factors. Results are intended to show specific areas at risk, not time-of-travel, nor any time of contamination. Because flow in karst is typically rapid, this study considers worst-case scenarios. Attenuation mechanisms, including sorption and biodegradation are not considered in this model.

Specific tasks to accomplish the main objectives are:

- Develop a conceptual model that is reasonably accurate, based on readily available data and explain why certain data were or were not used;
- Develop a model using GIS software to predict the advective routes of travel in a mantled karst;
- Organize all data needed to run the model for Clear Creek Basin, Washington County, Arkansas and provide example model runs in or near the basin;
- Explain how the model works and provide a simple user's manual; and
- Verify the model by comparing the results with actual dye and spill data.

LITERATURE REVIEW

Need for the project

Rapid population growth on a landscape underlain by karst features such as caves, sinkholes, and conduits within the shallow aquifers is characterized by numerous environmental and ecological problems (Beck et al. 1997). In Northwest Arkansas, karst features are becoming an increasing concern for environmentalists, housing developers, and city and state governments, especially with respect to siting urban development, landfills, transportation centers, septic tank use, sewage treatment plants and handling contamination problems already present (Stanton 1993). Several major projects in the area have been specifically engineered for the sensitivity of the karstic features of the area, such as the detour of Interstate 540 outside of the Cave Springs drainage area (Aley 1978). One example of the sensitivity in the area is that Cave Springs has the largest known population of the federally endangered blind Ozark Cavefish, *Amblyopsis rosae* (Brown 2000).

For this dissertation, areas in the mantled karst affected by advective transport were delineated to identify possible discharge points (springs) from point source contamination. These advective transport areas could be used to identify areas where leaks and spills of harmful material could contaminate or pollute wells and springs. Impact 5 of the Environmental Impact Statement (EIS) for Interstate 540 (previously named the Highway 71 relocation) near Fayetteville includes the subject of highway spills (Aley 1978). Aley states that one of the actions needed to reduce the seriousness of the groundwater impact from leaks and spills is to determine possible and probable discharge points for the contaminants. This would allow owners of wells and springs, who may be affected by a spill, to be informed of the possible contamination before the contaminants reached the water supply.

It was a major concern from the start of this dissertation to ensure that the model developed would be applicable to other areas subject to fractured mantled karst similar to that found in Northwest Arkansas. With an estimated 20 percent of the earth's dry-land surface, and 40 percent of the United States east of Tulsa, Oklahoma, being karst (White et al. 1995), the potential for tech-

nology transfer is great. The areas appropriate to apply the model would be limited to a fractured mantled karst having a topographical relief similar to Northwest Arkansas. The data in Fig. 1 lists major carbonate rock areas in North America.

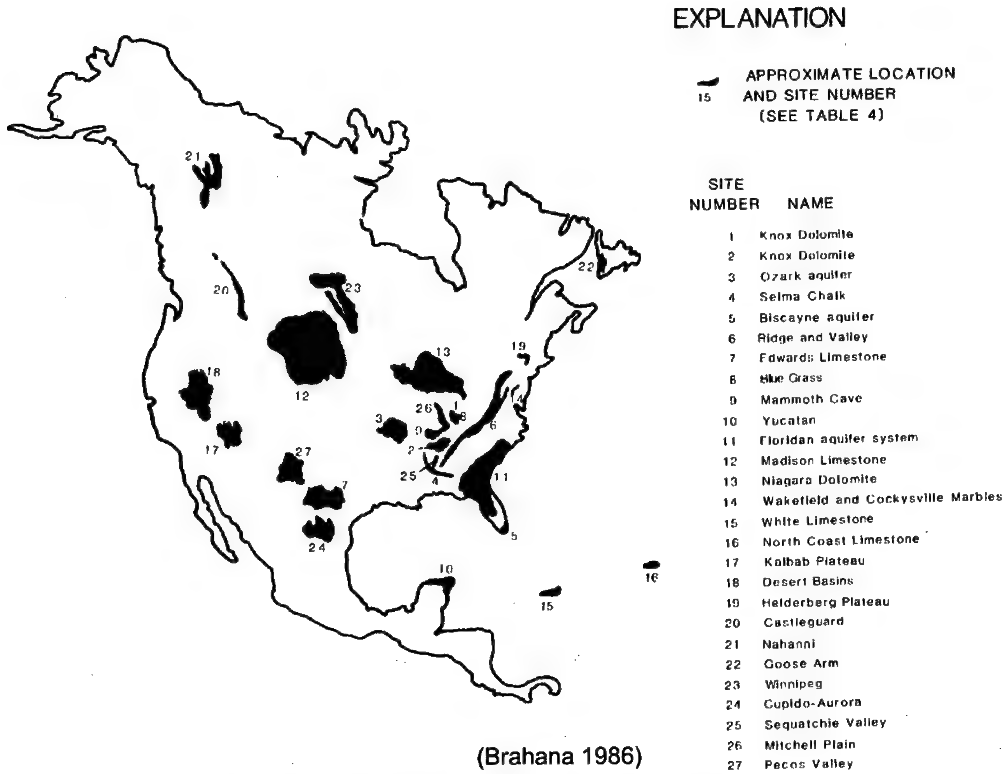


FIG. 1 Major Carbonate Rock in North America

Karst

The term "karst" is a comprehensive topographic term applied to limestone areas which possess a topography peculiar to and dependent upon underground solution and the diversion of surface waters to underground routes. Implied in this definition is the fact that carbonate rock, chiefly limestone, yields freely to the solvent action of water. Also, it is a known fact that the rate of solution is greatest when the water is charged with carbon dioxide (CO_2). Rain, as it falls to earth, collects carbon dioxide from the atmosphere, and as it soaks into the ground, it collects more carbon dioxide from decaying organic matter. Water heavily charged with carbon dioxide forms a weak acid, known as carbonic acid, that reacts with limestone and dissolves it. As the acid dissolves limestone, it forms a solution of calcium bicarbonate, and as long as carbon dioxide

exceeds calcium carbonate, the limestone continues to dissolve. However, when the water containing calcium bicarbonate reaches an opening such as a cave, it loses its carbon dioxide and deposits calcium carbonate in the form of columns or icicle-like forms called stalactites and stalagmites ("National Park Service" 2000).

Reaction of carbonic acid in the dissolving of limestone causes the cracks in limestone to become larger, fissures and joints are widened, and eventually the surface of the ground becomes pitted because of the formation of sinks. A large portion of the water that falls upon the ground in regions of limestone bedrock eventually finds its way into underground channels. In areas where solution of limestone is in evidence, the most characteristic topographic feature is the sinkhole, through sinking streams, caverns, resurgences, and other features attending underground drainage in limestone areas compose the karst assembly. Many of the features of the karst assembly are not distinctly topographic, or they are only occasionally present in karst terrain ("National Park Service" 2000).

Another smaller definition of karst: a solution-controlled landform type, characterized by an exclusive surface morphology, subsurface drainage and collapse features, which is specifically developed in soluble rock. These elements remain constant even though climate, structure and petrography generate greatly diverse surface features (Sweeting 1973).

The word *karst* comes from the Slovenian and Serbo-Croation languages. Kras is a regional name for the north-westernmost corner of the limestone area of the Outer Dinarides, behind the Bay of Trieste in Slovenian; this became the word, "karst" in geomorphology (Embleton 1984).

Karst Aquifers in the Study Area

Karst aquifers, by their very method of formation, are highly nonhomogeneous and anisotropic. Groundwater may flow in several different directions, depending on the height of the water table influenced by the instantaneous flow conditions in the area at a specific time (Aley 1978). Much like surface-water basins, but without the definitive boundary provided by topographic highs, groundwater basins may be delineated, although basin boundaries may shift with water levels and

piracy and flood-overflow routes across basin divides are common (White 1999). Bedding planes and preferred flow paths may be above the average water table; however, at high flow they may redirect water to different destinations than would occur during normal flow conditions. Curtis (2000) showed that dye-tracing studies in Northwest Arkansas do not simply follow topography. Land surface does not always predict groundwater movement, and groundwater basins do not necessarily coincide with surface watersheds. Groundwater flow in karst areas is concentrated along unpredictable, preferred flowpaths that are typically open and much more permeable than the surrounding rock (Brahana et al. 1999).

These variations in flow patterns support the belief held by many well respected researchers that karst hydrogeology does not lend itself to easy interpretation. Many, in fact, consider it unlikely that numerical tools and models will be developed that will accurately predict groundwater flow and transport in karst aquifers at less than regional scales (Brahana et al. 1999). Huntoon (1999) further states that karstic permeability tends to be the most anisotropic of all the permeability types found in nature. However, groundwater occurrence and movement in karst are intimately related to an integrated system of joints and fractures (Moore and Hinkle 1977). Major joints and fractures, which channel the bulk of the groundwater flow, typically are associated with lineaments (Hanson 1973; Moore and Hinkle 1977; Rezaie 1979). If the lineaments represent correlating fractures and joints, then those lineaments could be used to determine possible flow paths. A model that uses lineaments as the flow paths could therefore be developed to predict the advective transport through a fractured karst. In addition, using lineaments which can be remotely sensed and do not require expensive, full-blown, on-site studies, further simplifies the data required for the model.

Conceptual Models

Karstic carbonate aquifers are extremely heterogeneous and have a distribution of permeability that spans many orders of magnitude. They often contain open conduit flow paths with hydraulic characteristics more like surface streams than ground water. Karstic carbonate aquifers have highly efficient interfaces with surface water through swallets and springs. Characterizing

parameters include: area of groundwater basin, area of allogenic (more than two that are different) recharge basins, conduit carrying capacity, matrix hydraulic conductivity, fracture hydraulic conductivity, conduit system response time, and conduit/fracture coupling coefficients. The geologic setting provides boundary conditions that allow the generalized conceptual model to be applied to specific aquifers (White 1999).

A detailed description of a typical conceptual model for a carbonate aquifer is illustrated in Fig. 2. The conceptual model is an interconnected sequence of recharge areas, permeability

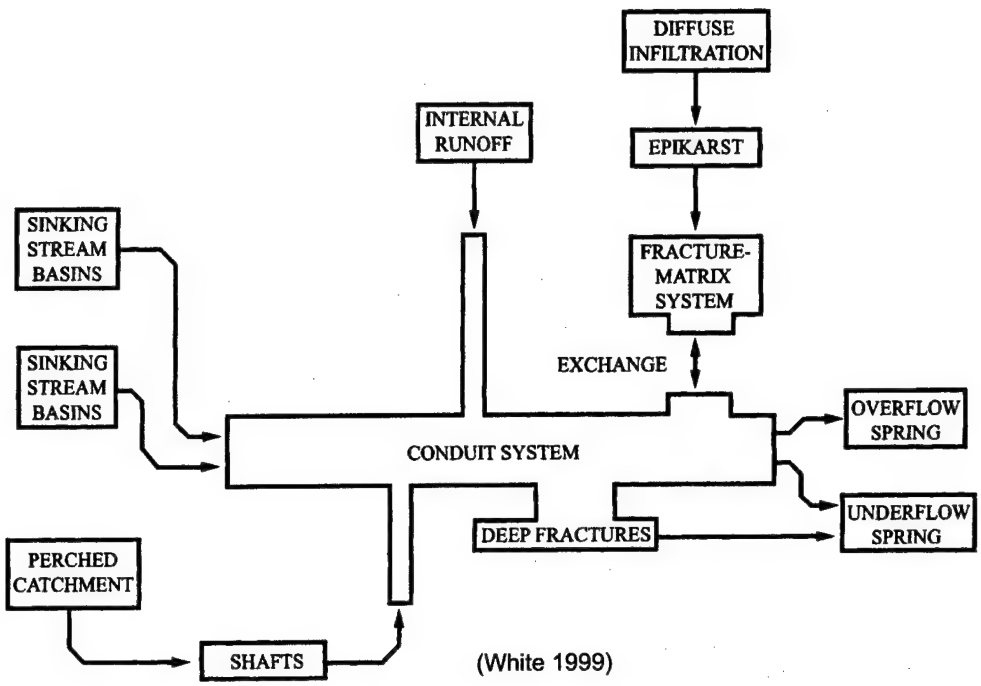


FIG. 2 Conceptual Model for a Carbonate Aquifer

distributions, and geologic substrates that collectively provide a visualization of the way in which water is added to the system, stored in the system, transmitted through the system, and discharged from the system (White 1999). White's conceptual model was used as the cornerstone for the software model developed in the study and discussed in the next section.

Conduit systems act as low-hydraulic-resistance drains, so that the flow field in the surrounding matrix and fracture system is directed toward the conduit rather than toward groundwater discharge zones on the surface. During base flow conditions, groundwater recharged from diffuse infiltration and groundwater stored in the fracture and matrix porosity will drain toward the conduit

system (Fig. 2). However during storm flows, the conduit system may flood to the roof and indeed establish a substantial piezometric head above the roof of the conduit. During intervals of storm flow, the flow field will reverse and water will move from the conduit into the surrounding fracture and matrix porosity (Fig. 3). The effectiveness with which these two systems are coupled, combined with the intrinsic hydraulic conductivity of the matrix and fracture systems, will determine the rate of movement of groundwater into and out of storage and also the base-flow discharge of the springs (White 1999).

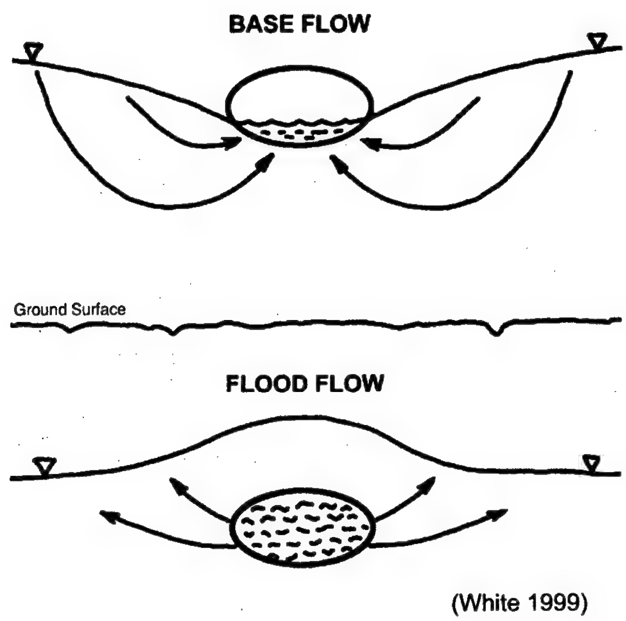


FIG. 3 Sketch Showing Exchange of Groundwater Between Conduit System and Fracture System During Base Flow and Flood Flow

Groundwater Recharge

Groundwater recharge in Northwest Arkansas is associated with discrete recharge (Aley 1978). Discrete recharge, typically in the form of stream piracy, also appears to be associated with lineaments (Aley 1978; Aley and Aley 1987). Discrete recharge, called concentrated recharge by some researchers, is the concentrated and relatively rapid movement of recharge water toward the water table (Aley and Aley 1987).

The majority of water storage and movement in the study area is through solutionally-enlarged openings. Much of the water movement through the soils and bedrock from the land surface into the groundwater system is along discrete pathways from discrete recharge zones. Water moving underground through discrete recharge zones and solutionally enlarged openings is not subjected to effective natural purification processes such as filtration or sorption (Aley 1978). In addition to the concentrated recharge, contaminants can be introduced by means of dispersed infiltration, non-point source pollution that also can be transmitted with minimal filtering (Smith 1993).

Linear Trends: Lineaments and Fractures

The definition of linear trends is restricted to natural linear features whose origins are not related to outcrop patterns of inclined strata or stratigraphic contacts. Man-made features such as highways, railroads, irrigation canals, and planted windbreaks are not included in the concept of a linear trend. Therefore, linear trends reflect zones of regional shear, bedrock joints, or more simply, discontinuities in the bedrock (Hanson 1973). The hydraulic characteristics of these discontinuities are much greater than the surrounding bedrock matrix, and they are a dominant control affecting groundwater flow (Brahana 2000).

Linear trends visible on aerial photographs can be related to topography, soil tones and vegetation. These linear trends can be divided into two major groups; lineaments and fracture traces. Fracture traces are natural linear features visible primarily on aerial photographs, are expressed continuously for less than one mile, and tend to reflect bedrock joints or small faults. In contrast, lineaments are natural linear features visible primarily on aerial photographs or mosaics and are expressed continuously for at least one mile, but may be expressed continuously or discontinuously for many miles. Lineaments tend to reflect regional shear zones resulting from deep-seated faults. These definitions (Lattman and Nickelsen 1958) are generally acknowledged in the literature--the distinguishing characteristic being one of length (Hanson 1973).

The lineament data used for the initial application of the model developed in this dissertation were collected as part of a masters thesis at the University of Arkansas (Hanson 1973). Appli-

cation of this model to other geographic areas requires input data from lineament studies. If no data are available for a specific study area, then additional studies in the area of mapping geologic fracture traces and lineaments will be needed (Lattman 1958; Lattman and Nickelsen 1958; Lattman and Parizek 1964; Wang 1989; Wladis 1999). The benefit of using lineaments is that they can be identified from existing remotely sensed data for most of the country and much of the world.

Lineaments/fractures/bedding planes and water movement

Lineaments have been studied and related to well production, spring discharge, and groundwater flow (Hanson 1973; Moore and Hinkle 1977; Powell 1977; Aley 1978; Willis 1978; Aley and Aley 1979; Ogden 1979; Rezaie 1979; Shinn 1979; Eddy 1980; Aley and Aley 1987; Leidy 1989; Williams 1991; Stanton 1993; Smith 1998; Brahana et al. 1999; Huntoon 1999). Although well production near lineaments has been disputed (Lattman and Parizek 1964; Ogden 1979), relationships between fracture traces, lineaments or solution channels in defining increased zones of permeability and porosity development for groundwater flow have been well supported and documented (Setzer 1966; Sonderegger 1970; Siddiqui and Parizek 1971; Hanson 1973; Coughlin 1975; Faulkner 1976; Parizek 1976; Boulton and Streltsova 1977; Feder 1977; Frohlich and Smith 1977; Mijatovic 1977; Moore and Hinkle 1977; Powell 1977; Wermund and Cepeda 1977; Aley 1978; Gaines 1978; Willis 1978; Eddy 1980; Aley and Aley 1987; Leidy 1989; Austin 1991; Williams 1991; Stanton 1993; Smith 1998; Annable and Sudicky 1999; Ford 1999; Huntoon 1999; Kastning 1999; Loper 1999; Meiman and Ryan 1999; Palmer 1999b; Smart 1999; White 1999; Worthington 1999).

Powell (1977) indicated that bedding planes *per se* are seldom a significant form of permeability as compared to joints in carbonate rocks in central southern Indiana. However, bedding planes may localize flow horizontally and over long periods of geologic time, details of microlithology and stratigraphy can have a huge impact on some types of karst flow. These types of flow systems, however, cannot be remotely sensed and account for most of the error of the model produced by this dissertation (Brahana 2000). Potential users of the model must determine if such errors are tolerable for the problem being simulated.

Joints are an important distinctive characteristic of most carbonate lithologies dependent upon unit thickness. Nearly all significant transmission of water in Powell's studies of central southern Indiana has been along joints within particular stratigraphic units rather than along bedding plane separations between such units (Powell 1977). Brahana (1997) seems to also support the theory that faults, fractures and joints are the dominant controlling factor of groundwater movement in Northwest Arkansas (Fig. 4). Although bedding planes are present and control some flow in Northwest Arkansas, the dominant geologic controlling features that can be remotely sensed are fractures and joints in combination with surface relief (Brahana 2000). The structural geology and tectonic setting define features that enhance the concentration of flow within the integrated ground-water system and may create hydrogeologic boundaries. Those features often have discernible surface manifestations which facilitate identification (Brahana 1997).

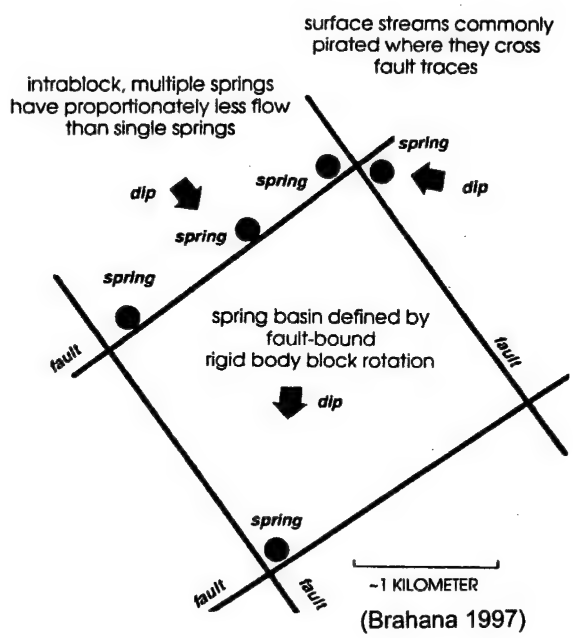


FIG. 4 Idealized Relation Between Faults, Framework Dip, Spring Basin, and Springs in the Springfield Plateau

Study Location and Hydrogeologic Framework

Clear Creek Basin (Fig. 5) located in Washington County, Arkansas, was selected for use in this dissertation because of past and current studies in or near the area including Stanton (1993)

which provided an excellent discussion of the stratigraphic overview, hydrogeologic setting, and structural geology of the relevant area. The study area used to verify the model is located in Northwest Arkansas in Washington and Benton Counties (Fig. 5). However, data acquisition for this project includes areas of Carroll, Madison, Benton, and Washington Counties in Arkansas. Several masters theses have been written concerning the hydrogeology, hydrogeochemical or geology in or near the study area, including geologists, engineers and geographers (Hanson 1973; Coughlin 1975; Hurley 1976; Gaines 1978; Willis 1978; Ogden 1979; Eddy 1980; Liner 1980; Muse 1982; Leidy 1989; Austin 1991; Williams 1991; Stanton 1993; Smith 1998; Al-Rashidy 1999). Other studies (Aley 1978; Aley and Aley 1987) that include hydrogeology in or near the study area were also reviewed .

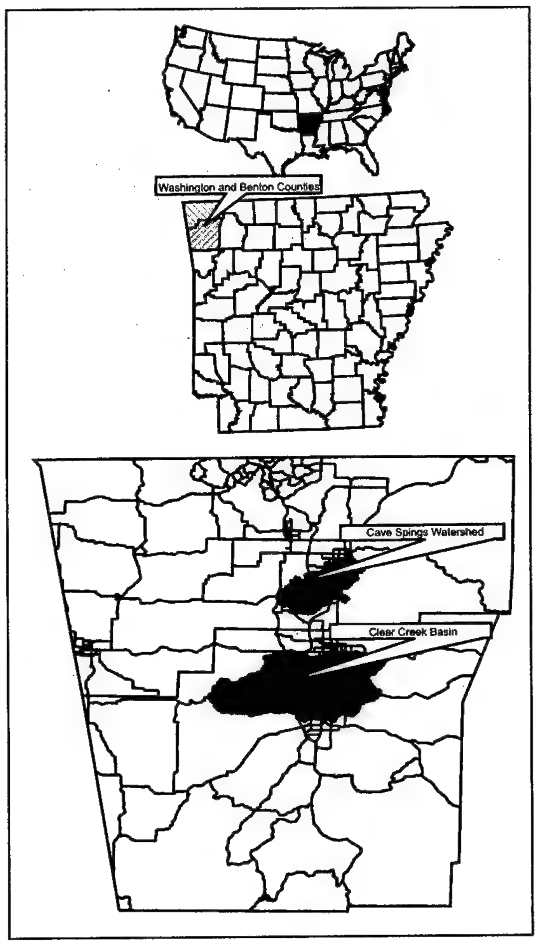


FIG. 5 Location of Study Area

The generalized stratigraphic column of northwestern Arkansas (Fig. 6) identifies the aquifers of the Salem Plateau, Springfield Plateau, and Boston Mtn. Plateau, and appropriate confining units that separate them. The majority of the study area is located within the Springfield Plateau. The Springfield Plateau (Fig. 7) surface is generally coincidental with the exposure surfaces of the Mississippian Boone and St. Joe Limestone Formations in northern Arkansas. Shale of the Devonian age Chattanooga Formation, the regional confining unit, generally underlies land surface, although it may outcrop in some stream valley floors within the study area (Stanton 1993).

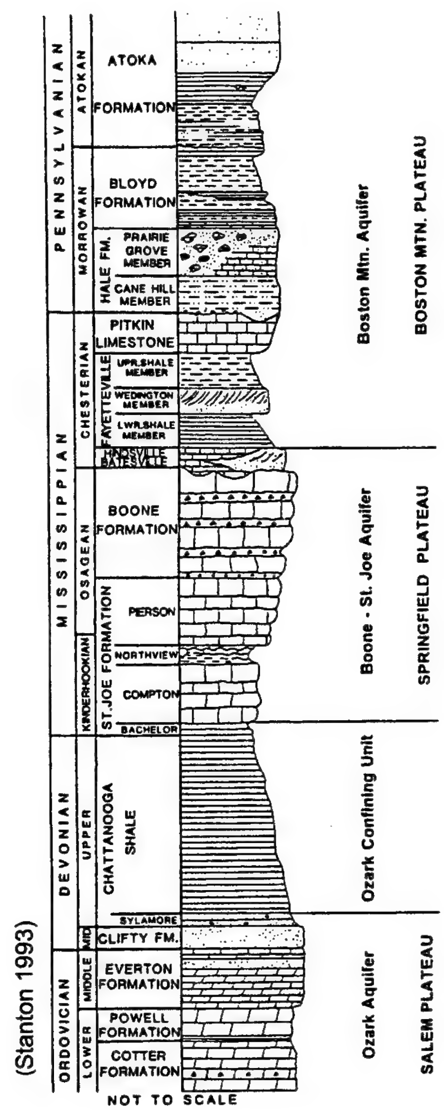
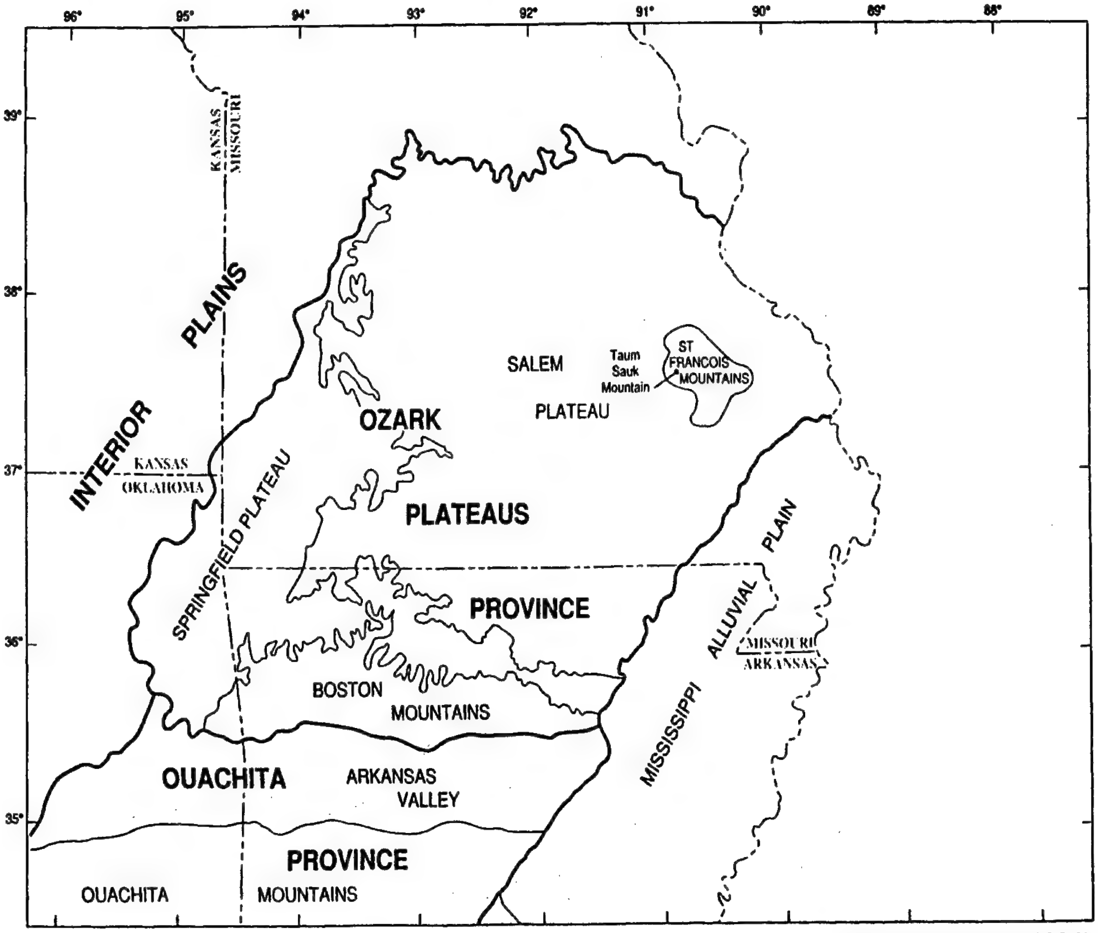


FIG. 6 Generalized Stratigraphic Column of Northwestern Arkansas Showing Relationships Between Stratigraphy and Hydrologic Plateau Surfaces

Low primary permeability and low primary porosity characterize the rock matrix of the Boone and St. Joe Formations. Secondary permeability of the Boone - St. Joe is dependent on the development of solution channels along fractures and bedding planes. This concentration of flow results in major anisotropy occurring along these preferential flow paths; site-specific flow paths are difficult to predict in the subsurface (Stanton 1993).



(Imes and Emmett 1994)

FIG. 7 Location of the Springfield Plateau

Dissolution in the Boone appears to be concentrated along the chert-carbonate contacts and along bedding planes, which generally are characterized by greater clay content and thus lower hydraulic conductivity. In the St. Joe, jointing controls the location of the vadose vertical dissolution channels and large phreatic conduits are observed. Jointing, coupled with the presence of a relatively chert-free carbonate unit, appears to promote the development of high transmissivity conduits within the St. Joe. The Boone Formation, with its fractured chert layers, often slowly col-

lapses into the underlying St. Joe voids to form sinkholes in the areas where the Boone is thin (Stanton 1993). These fractures may be associated with lineaments that can be remotely sensed.

Several have stated (Croneis 1930; Melton 1930; Quinn 1959) that forces associated with the Ouachita orogenies were largely responsible for folding and faulting in Northwest Arkansas (Gibbons 1962). These forces are the most likely cause of the fractures and faults in Northwest Arkansas that are associated with lineaments (Hanson 1973; Willis 1978; Rezaie 1979).

Models

Groundwater modeling efforts are generally one of two types: 1) those aimed at predicting the consequences of a proposed action, or 2) those used to test a hypothesis about a system. Models can be used in an interpretive sense to gain insight into the controlling parameters in a site-specific setting or as a framework for assembling and organizing field data and formulating ideas about the system dynamics. Models can also be used to study processes in generic geologic settings (Anderson and Woessner 1992).

Conceptual models, discussed earlier, are based on field observation and guided by knowledge of karst-forming processes. They are able to stand alone without mathematical or numerical analysis. *Analytical models* are derived from the functional relationships inherent in natural "laws" such as flow equations and conservation of mass. *Digital models* come in two forms: 1) commercial software for interpreting groundwater flow patterns and geochemical equilibria, and 2) specialized numerical models designed to investigate complex physical relationships, e.g. in the evolution of karst conduits. Digital models have almost entirely supplanted analog models, for example those in which resistor-capacitor networks or heat flow are used to simulate groundwater flow. *Statistical models* draw upon field evidence to allow quantitative predictions of the nature of karst by fitting the data to ideal distributions. *Scale models* are hardware reconstructions of field conditions, usually at reduced scale (Palmer 1999a).

Numerical methods such as MODFLOW, PLASM, and AQUIFEM-1 (Anderson and Woessner 1992) are used in much of the groundwater modeling today. However, these methods usually involve assumptions of homogeneity (Anderson and Woessner 1992), an attribute nor-

mally not associated with karst landscapes. Table 1. identifies the requirements for a typical numerical groundwater flow model. The data needed are extensive and realistically are almost impossible to obtain in a karst environment. Researchers have suggested, it may be unlikely that numerical tools and models that are also cost-effective and accurately predict groundwater flow and transport in karst aquifers at site-specific scales will ever be developed (Brahana et al. 1999). Most environmental problems in karst are predominantly site-specific in scope (Brahana 2000).

TABLE 1. Data Requirements for a Groundwater Flow Model

A. Physical framework of area

1. Geologic maps and cross-sections showing the areal and vertical extent and boundaries of the area.
2. Topographic map or DEM showing surface water bodies and divides.
3. Contour maps or DEM showing the elevation of the base of the aquifers and confining beds.
4. Isopach maps showing the thickness of aquifers and confining beds.
5. Maps showing the extent and thickness of stream and lake sediments.

B. Hydrogeologic framework of area

1. Water table and potentiometric maps or DEMs for all aquifers.
2. Hydrographs of groundwater head and surface water levels and discharge rates.
3. Maps and cross sections showing the hydraulic conductivity and/or transmissivity distribution.
4. Maps and cross sections showing the storage properties of the aquifers and confining beds.
5. Hydraulic conductivity values and their distribution for stream and lake sediments.
6. Spatial and temporal distribution of rates of evapotranspiration, groundwater recharge; surfacewater groundwater interaction, groundwater pumping, and natural groundwater discharge.

(Adapted from Anderson and Woessner 1992 (*Adapted from Moore 1979*)).

No natural system violates more basic assumptions or is less suited to predictive digital modeling than karst. The results discovered using any model should be used only as an idealized comparison with what is actually observed in the field. The discrepancy between observed conditions and the ideal model can be a great help in clarifying field conditions. The late James Quinlan, the world's most prolific karst groundwater tracer, repeatedly claimed that, "A single dye trace is worth a thousand digital models" (Palmer et al. 1999).

Current modeling in karst has for the most part been limited to predicting regional scale flow and transport (Imes and Eminett 1994; Zahm et al. 1998; Halihan et al. 1999; Wicks and Hoke 1999, Johnston et al. 1993) and used numerical methods for areas such as the Floridian and Edwards Aquifers. Various models (Rajaram et al. 1999) have also been used in determining the dissolution of the bedrock along fissures. All of the current karst modeling techniques require detailed information about the nature of the fracture or conduit network (Anderson and Woessner 1992).

Groundwater modeling software, for the most part, has been user unfriendly, demanded an unusually long and intensive learning curve, and required huge data sets. With the advent of Geographic Information Systems (GIS), an easier method of data management and software use could lead to faster advective transport predictions in fractured karst.

GIS is a tool for visually preparing, presenting, and interpreting spatial data (Tomlin 1990). GIS can be used to model many different types of data including finding travel costs, best route, and traffic flow. It can also be used to analyze paths (Ormsby and Alvi 1999). The model results are expressed as map cross sections, or 3-D projections (Tomlin 1990). The maps produced by a GIS are a visual representation of the spatial distribution of the data (Bonham-Carter 1994). GIS has been used to determine watersheds, calculate the network of streams over a surface, and estimating water runoff (ESRI 1996). Most karst researchers need to create models applicable for scales smaller than previously modeled (Zahm et al. 1998; Halihan et al. 1999; Wicks and Hoke 1999) by numerical methods. The regional models typically have grid spanning of about 10 km or larger, large enough to integrate the nonhomogeniety and anisotropy of the system.

Literature Summary

The literature referenced makes a clear case that the controlling factors for advective transport in a mantled karst are both lithology and structure, specifically fractures and joints. By associating the fractures and joints with lineaments, one can model the flow by using the lineaments as potential flow paths. By eliminating all other factors except the controlling factors, the data needed for model execution is drastically reduced. Flow rates in features such as conduits

(contributed by the controlling factors) are orders of magnitude higher than flow rates of the surrounding rock (Brahana 2000).

Engineers and scientists are inherently interested in complex applications using vast amounts of data and are relatively skeptical of simplistic applications that are parsimonious. Although the rationale of using lineaments and topography to predict advective transport in karst is simplistic, it is conceivably faster, cheaper and nearly as accurate as the more complex models that take years of data collection and still require calibration. The model developed for this dissertation may follow Pareto's Principle (Pareto 1974) wherein 80% of the predictions can come from 20% of the available data.

Having a model that requires only two data layers, DEMs and lineaments, makes the model very mobile, very cost effective, and very timely. Currently, seamless DEM data may be purchased from the United States Geological Survey (USGS). The only data required from fieldwork, if not already published, would be the lineament layer and reconnaissance hydrogeology.

METHODS

This dissertation's objectives are: 1) to integrate our understanding of flow and transport in a mantled karst setting and 2) to develop a simple model that will predict possible advective routes of travel in mantled karst in an economical, timely manner.

The scope was narrowed to exclude time of travel, diffusion, dispersion and sorption. The scope of the project was narrowed to focus on the main subject of advective transport in a mantled karst. Advective transport, also known as convection or advection, can be defined as the process of carrying dissolved solids along with the flowing groundwater (Fetter 1993).

Conceptual Model

The model developed in this study incorporates White's (1999) conceptual model with the *flow from surface* modification (Fig. 8). Earlier statements from White (1999) indicate that the potentiometric head can exceed the top of the conduit system as seen in Fig. 8a. This is a major concept that is needed when explaining how the model works. The modified graphic (Fig. 8b) illustrates how the conduit is brought to the surface where it releases the water in a flood flow situation. The illustration in Fig. 9 basically shows how the conduit could have a potentiometric head greater than the top of the conduit and shows how an outlet/spring can occur beyond a surface high. This also shows how interbasin transport can occur.

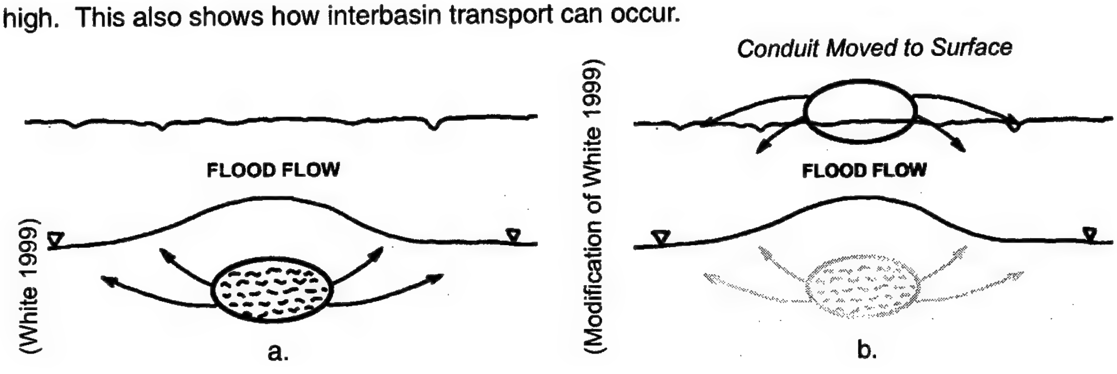
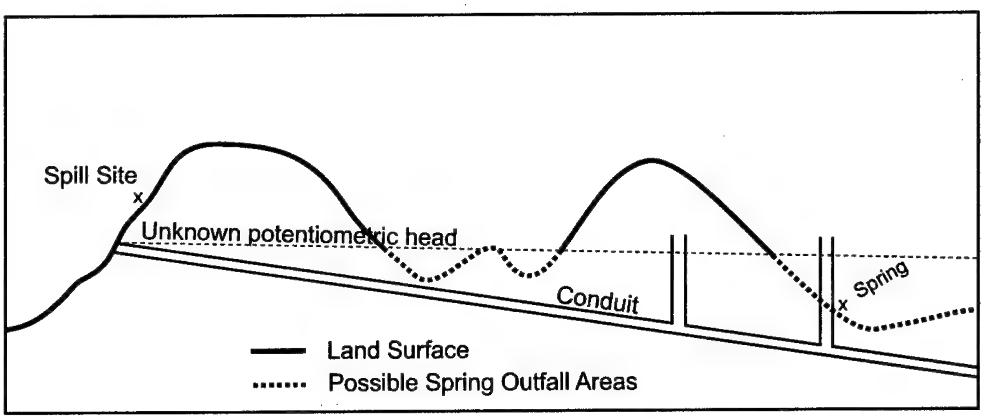


FIG. 8 White's 1999: (a) Conceptual Model and (b) Modified Model

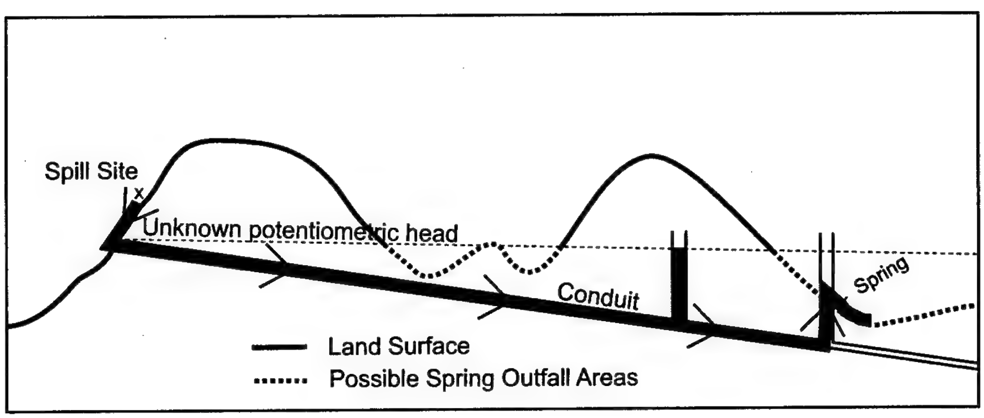
Simple Mechanics

The mechanics of the advective transport conceptual model developed in this study can be explained in two steps. In the first step, advective transport is allowed to flow over the surface

topography from a specific location. Each location is part of a grid and is surrounded by eight neighbors. Flow from that specific location to it's adjoining neighbors can be either equal (=) to or lower (<) than the specific point location's elevation (Fig. 10). New sites that the advective transport enters are then flowed from using the same = or < questions. The second step selects all lineaments that the flow crossed in the first step (flow across) and then brings those lineaments to the surface and flows from those locations using the = or < questions as seen in Fig. 11. Note that areas having an elevation of 101 in Fig. 11 are not selected because 101 is higher than the initial spill point of 100, thus 101 is not included in the spill point file.



a.



b.

FIG. 9 Potentiometric Head in Conjunction with Conduit Flow:
(a) Before Spill; (b) After Spill

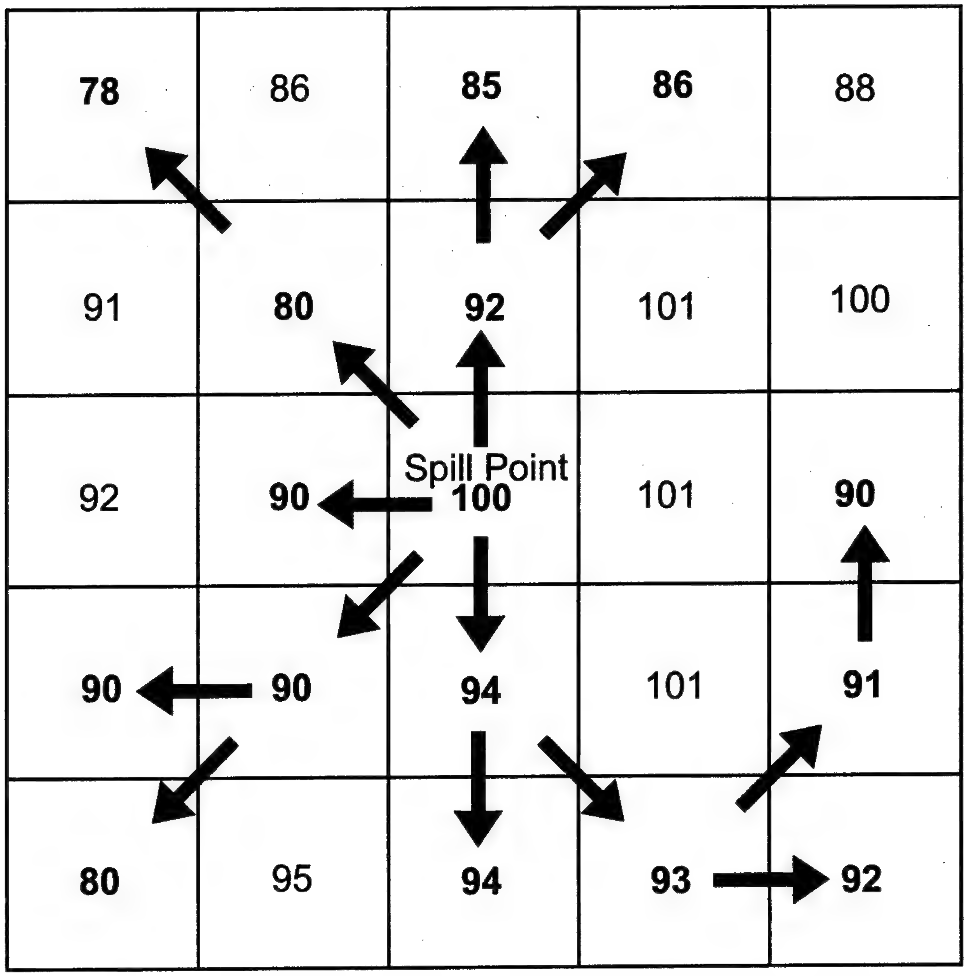


FIG. 10 Flow from Spill Point (Numbers Represent Elevations)

Mechanics used in the Model

The following explains the mechanics of the advective transport conceptual model and how it incorporates the scripts:

1) The model predicts overland flow by querying the initial spill point location's neighboring points and determining whether they are equal to or lower in elevation than the current point location. If the neighbors meet those requirements, then the model verifies that they have not been selected before. The "have not been selected before" eliminates the continues loop that may form if the question is not asked. If any of the neighbors are equal to or lower and it is the first time their cell has been selected, those points ask their neighbors the same questions. This operation is repeated until a previously selected distance limit has been reached. This will produce a series of

points making up an overland flow file containing point data that are tagged if they have met the flow requirements previously discussed.

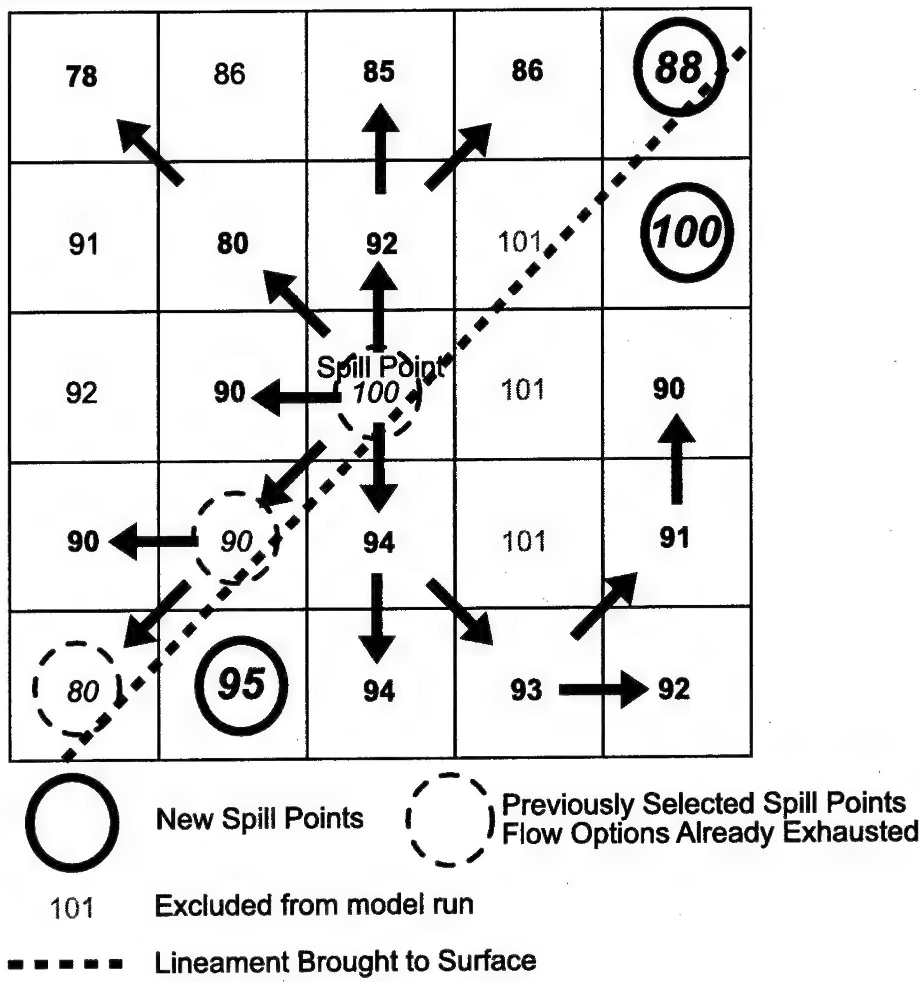


FIG. 11 Lineament Making New Spill Points

2) Lineaments that intersect the overland flow from Step 1 are selected and used as a spill point running along the entire length of the lineament. However, in this step, only areas of the lineament that are equal to or lower in elevation than the initial spill point are used to identify new spill points. Basically, the water is brought to the ground surface using the concept of the higher potentiometric head and then released to flow in the same manner as in Step 1. It should be noted that the direction of flow through the lineament is undetermined by the data used, thus the entire length of the lineament that is below the spill point elevation is used in this step. The spill elevation is used in place of the unknown potentiometric head to ensure worst case advective transport and to eliminate the need for water table data. The illustration in Fig. 12 shows the area in which the

model would release flow to the surface, and it is labeled *Areas at risk of contamination*. In the model, flow will be released to all areas along a lineament that are equal to or below the current spill point elevation. The elevation of the overland flow contact with the lineament (conduit) is not used in the model. This is to account for possible short circuiting (undocumented fractures) that may occur above the documented lineament (Fig. 13) and the dynamic nature of the unknown potentiometric head.

3) Step 2 can be repeated to add new lineaments to the model run. This is done if new lineaments cross the new flow path and could contribute to the advective transport.

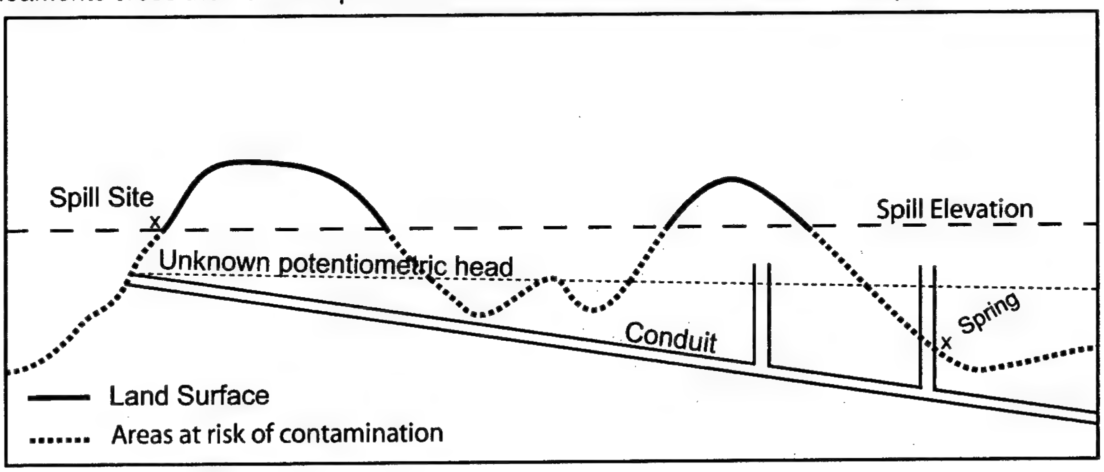


FIG. 12 Area Used as Lineament Flow

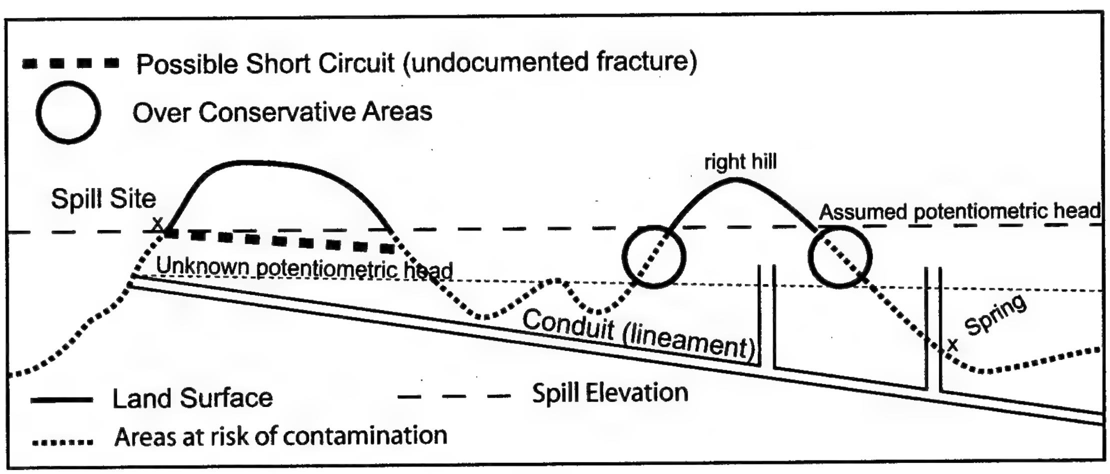


FIG. 13 Example of Short Circuit

The model may be over-conservative in some areas. For example, the circled "areas at risk" on the right hill of Fig. 13 would typically not be subject to contamination by the spill at the "Spill Site" in the figure. However, due to the dynamic nature (rising and falling) of the unknown potentiometric head, these areas were left in the model run.

The user (karst hydrologist) of the model may want to apply each lineament individually and subtract out areas above the documented lineament as possible contamination areas; however, this would lead to a less conservative model prediction. This is not a "black box" model and should not be used by persons who are not well-versed in karst hydrology.

It may also be helpful to read the User's Manual (Appendix B) after reading the rest of this section to show how the software model runs. The manual guides the reader step by step through an actual model run.

Data

Certain data that were extremely dynamic, contributed little to the overall outcome, or were too costly or too time-consujing to acquire were excluded from this dissertation.

Data not used

Epikarst

The components that make up the epikarst were excluded from the model due to its variability over an area and the fact that the recharge to the groundwater can be rapid and bypass any effects that the epikarst may have.

A contaminant from an actual fuel spill in 1971 traveled over two miles within 24 hours, killing 75,000 trout ("Gasoline Blamed in Fish Kill" 1971). This actual example along with the previous discussions on rapid infiltration led to the exclusion of diffusion, dispersion and sorption. However, these components are real and the user of this model should be aware of these limitations. By not including these parameters, the time-of-travel and time-of-concentration are excluded as an output of the model.

Bedding Planes

Bedding planes can play a role in groundwater movement. However, collecting the data for a perfect bedding plane layer to include in this type of model would be very labor intensive,

costly and for the most part, impossible to acquire. Fractures acting as conduits normally localize the flow, thus act as a major controlling feature that can be remotely sensed using different types of data including topographical maps, areal photos and satellite imagery. Even though the bedding planes may provide a mode of advective transport, the fractures localize that flow by acting as a collection system similar to a city's storm water drainage network. The localization of the flow by the fractures greatly reduces any errors that are associated with the exclusion of the bedding planes. However, exclusion of this data layer may account for most of the error that may be associated with the model.

Confining Layer

The dominant confining layer for the study area, the Chattanooga shale, was initially considered for use as part of the project; however, it was rejected as a data source after the draft model runs. The first model runs seemed to provide acceptable data output without the need to refer the confining data layer. By eliminating the confining layer as a data source, the model became much easier to move to other locations and kept with the original objectives of simplicity.

Water Table

The water table data were excluded because of its dynamic nature in the study area as discussed in the literature review. The layer would also be distorted by the kriging that would be needed to provide a complete coverage layer. The model uses the surface topography data as the water table layer which is more conservative and readily available from the USGS.

Data Used

Lineaments

The lineament data were acquired from Hanson (1973). Hanson included a fold-out map that included the lineaments associated with state and county boundaries along with the outlines of major cities. This map was scanned using a Visoneer 6100 scanner and saved as a Tag Image File Format (TIFF or Tiff) file. A copy of the scanned image from Hanson (1973) is shown in Fig. 14. The Tiff file was brought into ArcView for georeferencing so it would align with the DEM data and the Georeferenced Tag Image File Format (GeoTiffs) topographic maps, discussed later. To accomplish this, a new line shape theme was created and each lineament was redrawn over the

lineament Tiff. Each lineament has only a horizontal reference. No vertical references are associated with lineaments. The county and state boundaries were created and traced on a separate data layer. These two layers were then warped to the GeoTiffs, hence, georeferenced, and saved as a shape file (Fig. 15). This file could then be brought into ArcView to be properly aligned with the DEM and GeoTiff data.

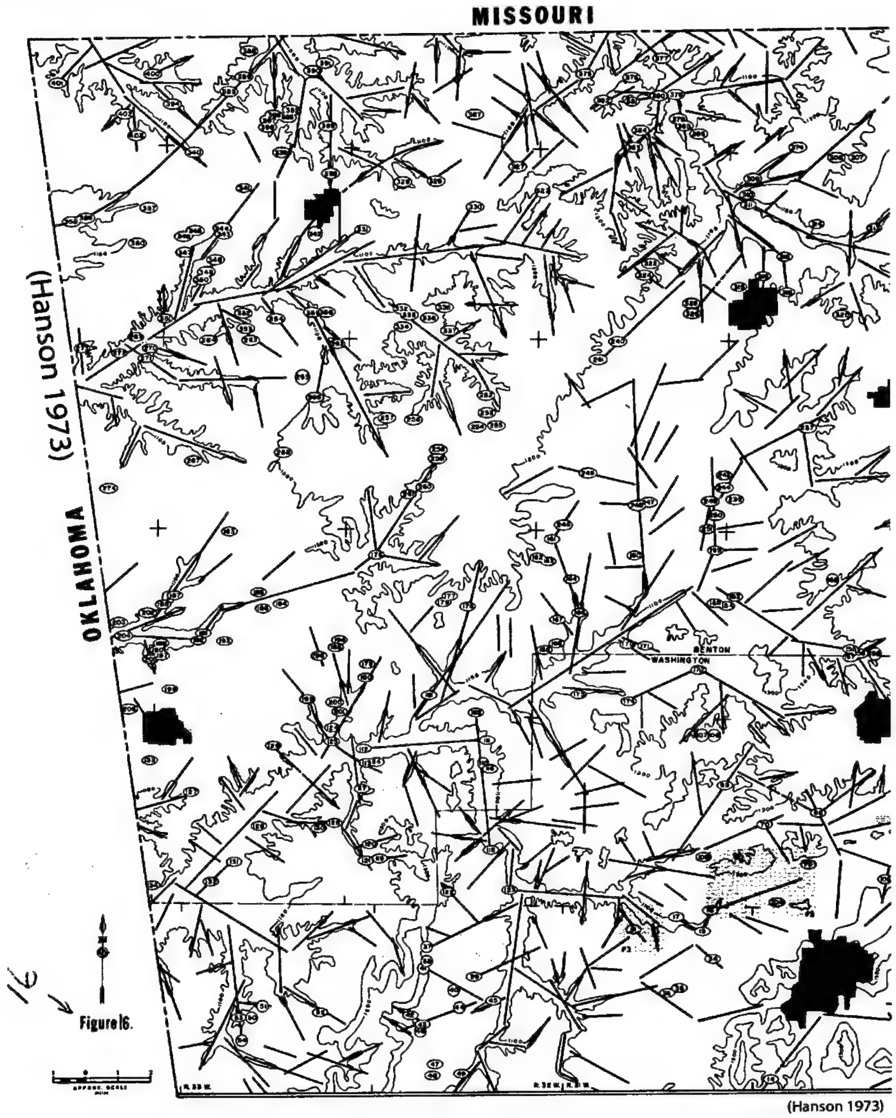


FIG. 14 Foldout Map in Hanson's 1973 Thesis, Page 34, Showing Lineaments Documented During His Research

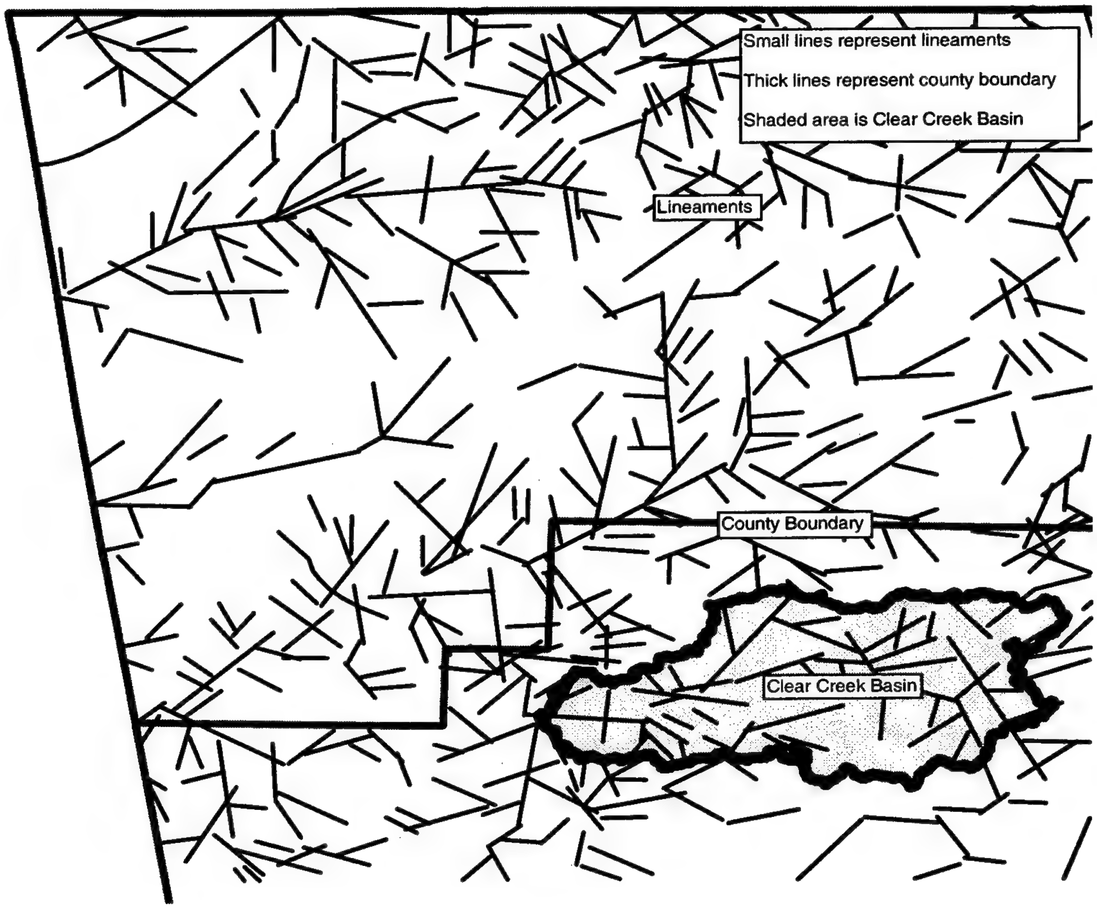


FIG. 15 Lineaments and County Boundaries Georeferenced Including Clear Creek Basin in the Shaded Area

DEM

The DEM data used for the project were purchased from the USGS. A detailed explanation for the National Elevation Dataset (NED) is included in Appendix A. This NED data set has been manipulated and is a much more friendly data set to use than the freely available DEMs. The free DEMs must be mosaicked together if more than one quadrangle is needed, and the quality is poor compared to the new NED data. The graphic in Fig. 16 shows the difference in data quality of the free DEMs versus the NED DEMs.

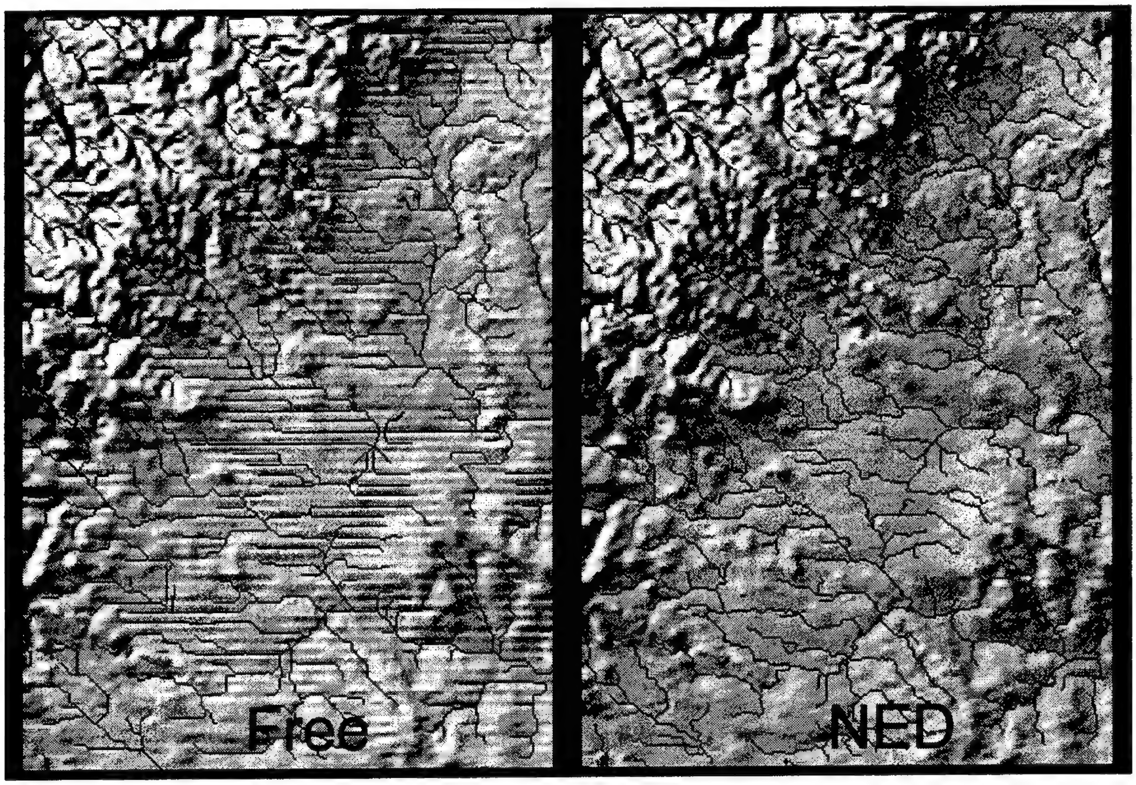


FIG. 16 Data Quality of Free DEMs vs. NED DEMs, Source USGS

GeoTiffs

The background layers used for this project were GeoTiffs obtained commercially from LandInfo (http://www.landinfo.com). These GeoTiffs are USGS 7.5 minute series (topographic) maps that have been scanned in at a 250 dots-per-inch (dpi) resolution and georeferenced using the originating map's datum. Although these commercially available GeoTiffs were used, there are freely available Digital Line Graphs (DLG)s on the Internet at the time of this document's writing.

These three data layers (lineaments, DEM, and GeoTiffs) are all that is needed to run the model developed in this study. A location data file could be substituted for the GeoTiff data. For example, a text file containing the latitude and longitude of a specific location could be brought into

ArcView as a reference point. The illustration in Fig. 17 shows each data layer and how it incorporates with the conceptual model.

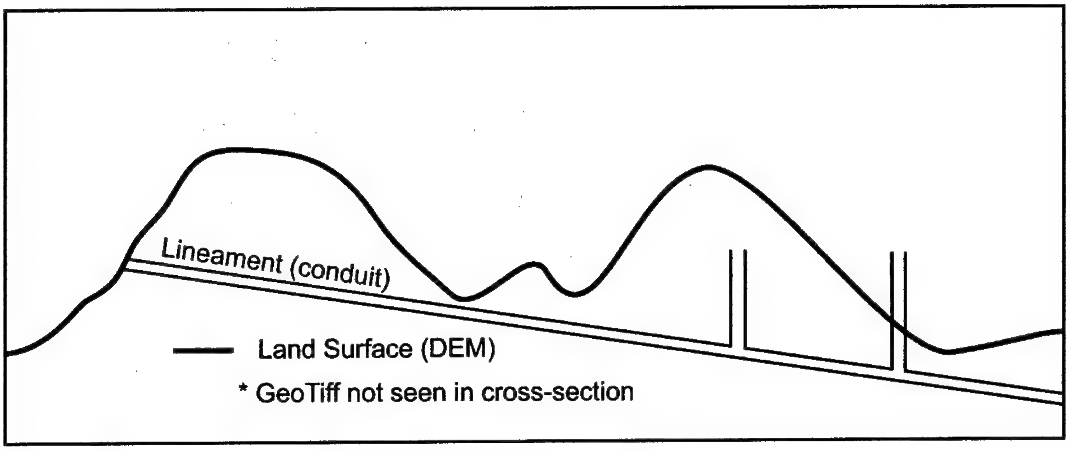


FIG. 17 Cross-section of Data Layers

GIS

During the conceptual modeling stage of the project, several software applications were considered to model advective transport through the fractured mantled karst. Since existing groundwater modeling software is not easily (if at all) adaptable to a karst setting, typically includes a steep learning curve and requires excessive data input, other alternatives were considered, including GIS.

The three data types discussed earlier included vector (lineaments), raster (DEM) and image data (Fig. 18). Two of the data layers needed for the model were readily available in a GIS format. The only exception was the lineament data layer that needed to be digitized and georeferenced. Since data were available in GIS format and GIS software is relatively simple to learn, it was decided to use GIS as the model's base software.

Once GIS was selected as the desired modeling method, a software package appropriate for the data formats had to be found. Although several software applications were reviewed, including ArcView with Spatial Analysis, GeoMedia and MFworks, the ability of the software to be used with multiple data types was the primary determining factor. ArcView with Spatial Analysis

was selected as the software for this model based on the ease it provided for working with all three data types in one package.

FIG. 18 Three Data Types Lineaments, DEM and GeoTiff Associated with Clear Creek Basin and the Washington Benton County Line

Programming

ArcView includes a script (programming) language called Avenue. This language is quite extensive and offers the ability to work with vector and raster data simultaneously. With the aid of Mr. John Wilson from *The Center for Advanced Spatial Technologies* (CAST), University of Arkansas, the initial concepts of applying the conceptual model to the data using ArcView were defined. At first it was thought that the vector data could be converted to a raster form and the model could be written to model the data in a raster format. After extensive script trials, it was decided to move the raster data to a vector point data set and run the model using vector points. The decision to

use vector data may have lengthened the model's execution time, but it also allowed scripts to be written that mirrored the conceptual model.

Scripts

Several scripts were written during the project, including *spillpoint, flowdown, onecellfill, makeshape*, and *flowup*. These scripts ares summarized in Table 2. The initial program, *spill-point*, Appendix C, was written to do the following:

1) Make a point shape file that included the spill point location and add to the View.
2) Clip the DEM into a circle at a specified distance eliminating all data higher than the spill point elevation.
3) Convert the DEM to a point shape file including two tag fields to be used in the model run that would be named *Tag* and *Tag1* and the elevation in the *Grid_code* field (Fig. 19).
4) Run the point data using the = or < concept and tag the *Tag* field with a number, representing the iteration number, if it met the flow requirements.
5) Provide the point shape file with selected points that had the *Tag* field tagged from step 4 and added to the view.

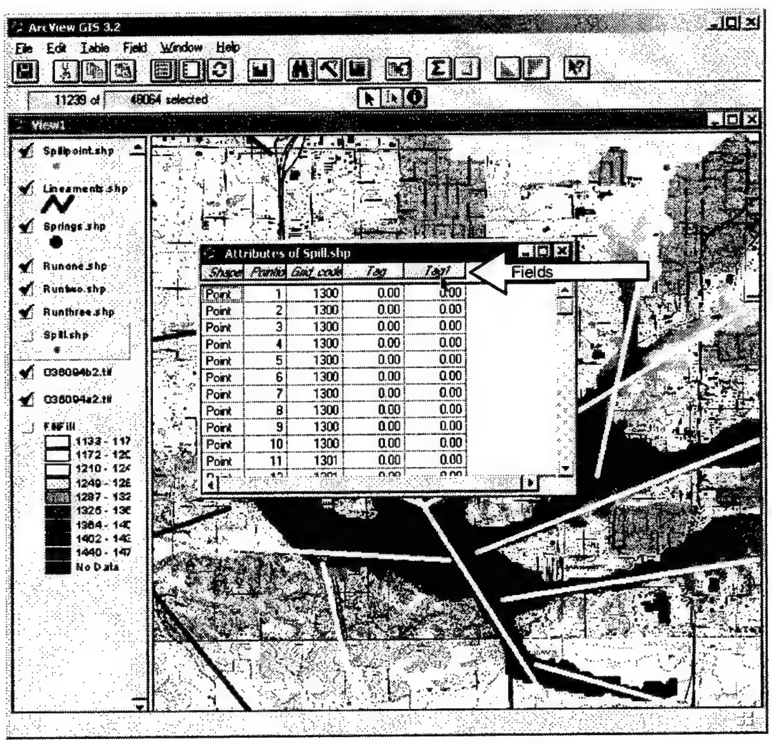


FIG. 19 Attributes of a Sample Project Showing Tag and Tag1 Fields

TABLE 2. Scripts Created For Use with the Advective Transport Model

Script	Button	Purpose and Use
Spillpoint		Used to start a spill from a specific point location. It also creates a point shape file containing to tag fields *Tag* and *Tag1*
Flowdown		Used after spillpoint or makeshape and will spill down from multiple points. The points spilled from are the shape points that have been selected
Flowup		Used after makeshape and will create a springshed starting from and using all points that have been selected
Makeshape		Make a point shape file out of a DEM that contains the *Tag* and *Tag1* Fields
Onecellfill	No Button	Used to fill one cell sinks left over when using the *hydro* sample extension included with ArcView

The *spillpoint* script does not use any lineament data and only includes overland flow from the spill point. The second script written, *flowdown*, Appendix D, included the ability to spill from multiple points such as along a lineament, and includes the following:

1) Flow using the = or < from all selected points and tag field *Tag1* with any newly selected points

Before using the *flowdown* script, the data must be manually manipulated so all points in the file located near lineaments and near the overland flow data generated in the *spillpoint* script are selected.

The third script, *onecellfill*, Appendix E, was written to fill one-cell-sinks. The DEM data needs all sinks filled to run properly. If a one cell sink is left, the flow way suddenly stop because the < or = question will not be satisfied. ArcView includes a sample script that will fill all sinks except for one-cell sinks. *Onecellfill* will fill all the one-cell-sinks left after running the sample script. The script includes the following:

1) Filling all one cell sinks left after filling the sinks using the hydro sample extension included with ArcView

The fourth script, *makeshape*, Appendix F, was written to provide an advanced user with the ability to manually control the area size and provide initial multipoint spill locations. The script, however, does not exclude any data, so elevation should be considered when using this data layer in model runs. The script includes the following:

1) Creates a point shape file of the DEM and creates the *Tag* and *Tag1* fields for use when using the downhill or uphill scripts.

The final script, *flowup*, Appendix G, was written to examine possible springshed areas and has the < changed to > in the script. This script was written at the request of the United States Environmental Protection Agency (USEPA or EPA) and other researchers at the University of Arkansas at Fayetteville.

Project File

The project file contains the five scripts listed above pre-loaded. The scripts could be loaded by the user into a new project file if so desired. Remember that all but the *onecellfill* script have been written to be executed from an Apply event (applied to a button). Further information on the Apply event is located under Help menu in ArcView.

RESULTS AND DISCUSSION

This section will be devoted to general practice of running the software model (scripts), data output and discussion of the model runs. Model runs will be broken into three types of applications. The first type of application of the model will be generic runs, showing examples in Clear Creek Basin. These are designed to give general views of data output the model will produce. The second series of model runs will show two actual applications using historical data from a fish kill at Johnson, Arkansas, and a dye test at Logan Springs, Arkansas. The third series of model runs illustrates how the model can be used to generate springsheds. It is important to note that the springshed modeling application (*flowup*) was introduced after the original objectives for the dissertation were defined. However, because the USEPA and other researches expressed an interest in this model application, *flowup* was included in the dissertation.

The software model was created and used for data processing using the following equipment:

Hardware/Software

Printer

Laser	Lexmark Optra T612N with 80MB of Memory

Hardware

Motherboard	ABIT BP6
CPU	Intel PIII 700
Memory	256MB PC133
Graphics Card	Matrox 400G DualHead
Monitor	ViewSonic P815
Drives	Iomega Zip 100
"	Toshiba DVD-ROM SD-M1212
"	Pioneer CD-ROM DR-U16S SCSI
"	YAMAHA CRW6416S SCSI CDRW
"	WDE18310 ULTRA3 SCSI Disk Drive
SCSI Controller	Tekram DC-390U2W
Ethernet Adapter	Linksys LNE100TX Fast Ethernet Adaptor
Sound	Creative SB Live! Basic

Software

Operating System	Windows 2000
GIS Software	ArcView 3.2 with Spatial Analyst 2.0
Word Processing	FrameMaker 6.0
Graphics	Illustrator 9.0
"	Acrobat 4.0

General practice when running the model

Spillpoint

The *spillpoint* script along with all of the other scripts are discussed in the Methods section under Scripts. The *spillpoint* script is the easiest to run and needs very little data preparation. The data preparation includes filling the sinks of the DEM and converting the DEM to an integer. If the spill area is near a topographical high, the user may want to zoom in and review the DEM to ensure that the GeoTiff matches the DEM and that the spill will flow in the appropriate direction(s).

Flowdown

The *flowdown* script is normally run after the *spillpoint* script has finished. It can also be run after the *makeshape* script has converted a DEM to a special point shape file. Creating a separate lineament line file and including only the lineaments or parts of lineaments that would be used in the model run produces a more accurate data output. The most conservative modeler could use all of the lineaments in a particular area of study. This would however, create a much larger coverage area and may not provide the most accurate output that could be accomplished.

By examining the topographical maps and reviewing spring locations and other pertinent geological information, a karst hydrologist could make specific decisions on which lineaments or parts of lineaments should be used. This model should not be run as a "black box", it should be used only by hydrologists who are well-versed in karst hydrology. Also, at the discretion of the modeler, new lineaments may be added if there is evidence that a lineament or conduit flow at a specific location was not documented in the original lineament study.

Flowup

The *flowup* script is run after the *makeshape* scripts and has the same restraints as the *flowdown* script discussed above. When running the *flowup* script, each lineament in the area should include documentation to explain why it was or was not used. This may help eliminate any possible bias in the model run and ensure reproducibility.

The *flowup* script is very sensitive to the data selected in the model run. The modeler should not rely on the GeoTiffs alone as the target spring location. The DEM should be made viewable and zoomed to ensure proper placement of the selected points to initiate the model. For

example, the spring (Stroud Spring) in Fig. 20 is shown as a black dot. If a point left of the spring (three blocks or 90 meters) was selected as the spring, the whole basin for that stream would have been included in the results of the springshed of Stroud Spring and would have greatly enlarged the springshed area.

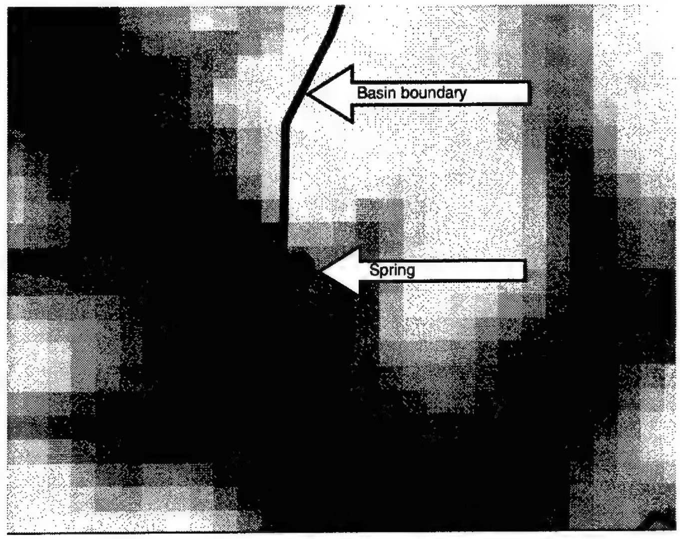


FIG. 20 Close up of Stroud Spring, DEM, and Springshed Boundary

Other elements may play a part in the initial run of *flowup.* Some springshed model runs may be executed by selecting only the spring location and running the script. However, in the case of Cave Springs, lineaments had to be associated with the spring, otherwise the springshed area would have been very small (0.29 km^2). The topography near Cave Springs, as seen Fig. 21, will limit the flow up. Cave Springs is a very good example showing that lineaments (Fig. 22) must be associated with springs to ensure a proper springshed boundary. Brahana (2000) also suggested that springs are produced by localized flow that is normally associated with fractures/faults, and that bedding planes normally produce seeps that form along a specific bedding plane.

If no lineaments are associated with a spring that is going to be modeled using the *flowup* script, it may be necessary to produce phantom lineaments for use in the model to account for the undocumented fractures that are most likely associated with the spring but were not remotely sensed. These new lineament(s) should be placed in a new line shape file to keep the phantom lineaments from being included with the original researched lineament shape file. The original lin-

eaments that may be used for the model run could then be redrawn in the new lineament shape line file.

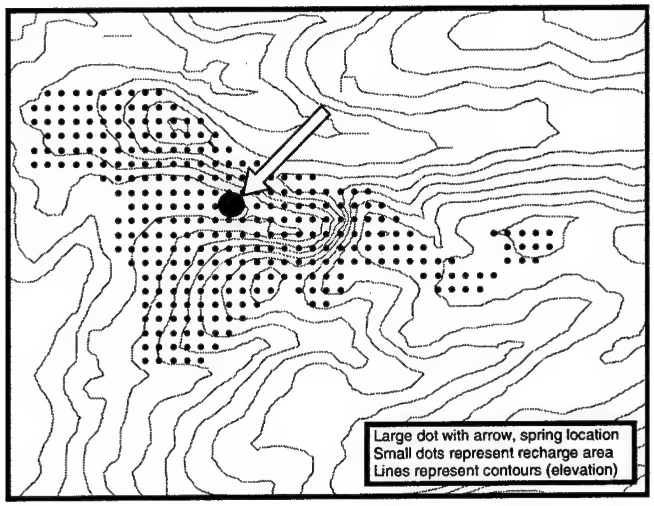


FIG. 21 Cave Springs Run with No Lineaments

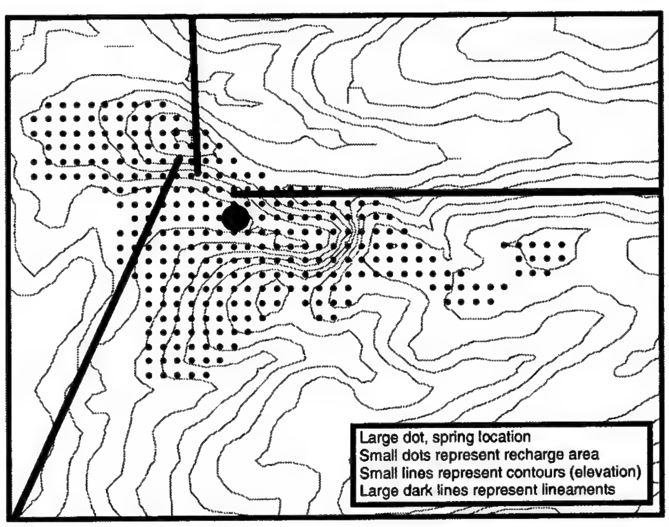


FIG. 22 Cave Springs with Lineaments That Would Be Used in the Next Model Run

Example Runs, *spillpoint* and *flowdown* scripts

Example Runs

Model runs for areas in or near Clear Creek Basin have been included to show how different shapes can form when the model is executed. The model runs vary from simple lines to complex spreads. The model runs in Fig. 23 show a variety of different types of output data along with lineaments and faults in the basin. One of the model runs in which the spill was originated in a stream is illustrated in Fig. 23. Here the spill fills the contour of the stream and is shown as a skinny white line (Example A), Fig. 23. Example B in Fig. 23 identifies the two main components associated with the model run: 1) the run area, made up of elevation points below or equal to the selected spill point, and 2) the overland flow that the model produced. The run area represents locations below the spill point within the radius set by the modeler during the model execution. Example A does not show the spill point which is located in the center of the circle; however, the Savoy run one and Example C (Fig. 23) show the spill points for those runs. All model runs shown in Fig. 23 are modeled using only the *spillpoint* script. The s*pillpoint* script shows overland flow and does not include lineament interaction. These model runs were modeled in the same manner as shown in the User's Manual, which was constructed as part of the dissertation and is included in Appendix B. When referring to the User's Manual the reader should be aware that Fig. 23 models were stopped after the initial *spillpoint* run.

Savoy

The graphics in Fig. 24 - Fig. 26 show sample model runs at the *Savoy Experimental Watershed* which is located at the very west end of Clear Creek Basin and is owned by the University of Arkansas. The Savoy model runs have been modeled using both the *spillpoint* script and the *flowdown* script; *flowdown* includes the lineament interaction. When referring to the User's Manual the reader should be aware that the Savoy model runs were stopped after the first *flowdown* run.

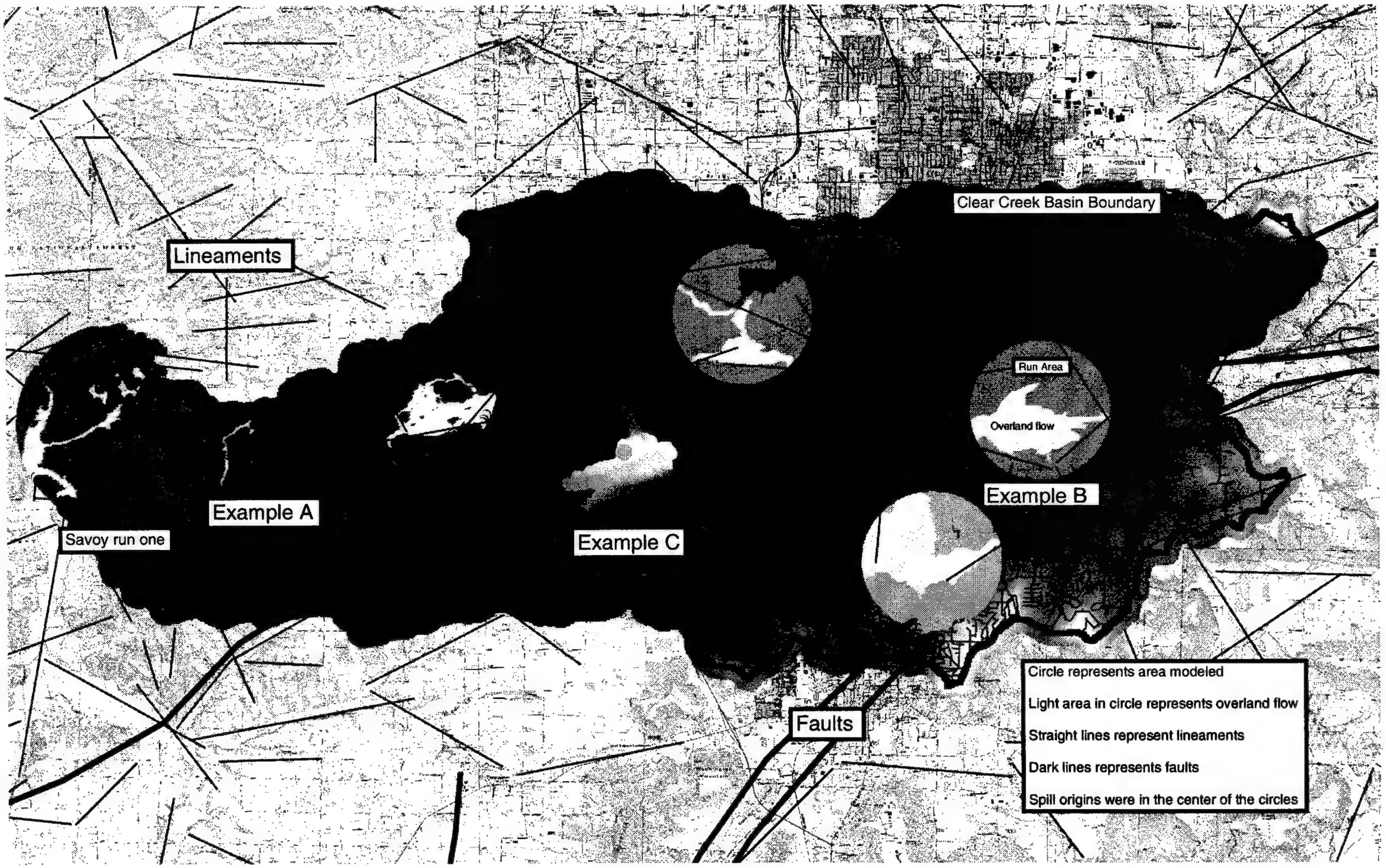


FIG. 23 Various Model Runs in Clear Creek Basin Along with Lineaments and Faults

The two model runs at Savoy show typical direct overland flow with some influence provided by the *flowdown* script using the lineaments. In each run the flow begins at the spill point and flows downhill, resembling the natural flow patterns. The color gradient shown in these model runs range from higher elevations (lighter color) to lower elevations (darker color), as seen in Fig. 24 - Fig. 26. The graphic in Fig. 24 shows mainly overland flow. The graphic Fig. 25 illustrates how interbasin transport can occur when lineaments are used. The second model run at Savoy (Fig. 25) is the most interesting because the spill site was atop a ridge and it provides an example of how multiple paths may occur from a single spill site. The second run at Savoy also shows that interbasin transport may occur. The initial spill was outside of the Clear Creek Basin, but after running the model, the spill flowed from a lineament and spilled over and into the neighboring Clear Creek Basin watershed.

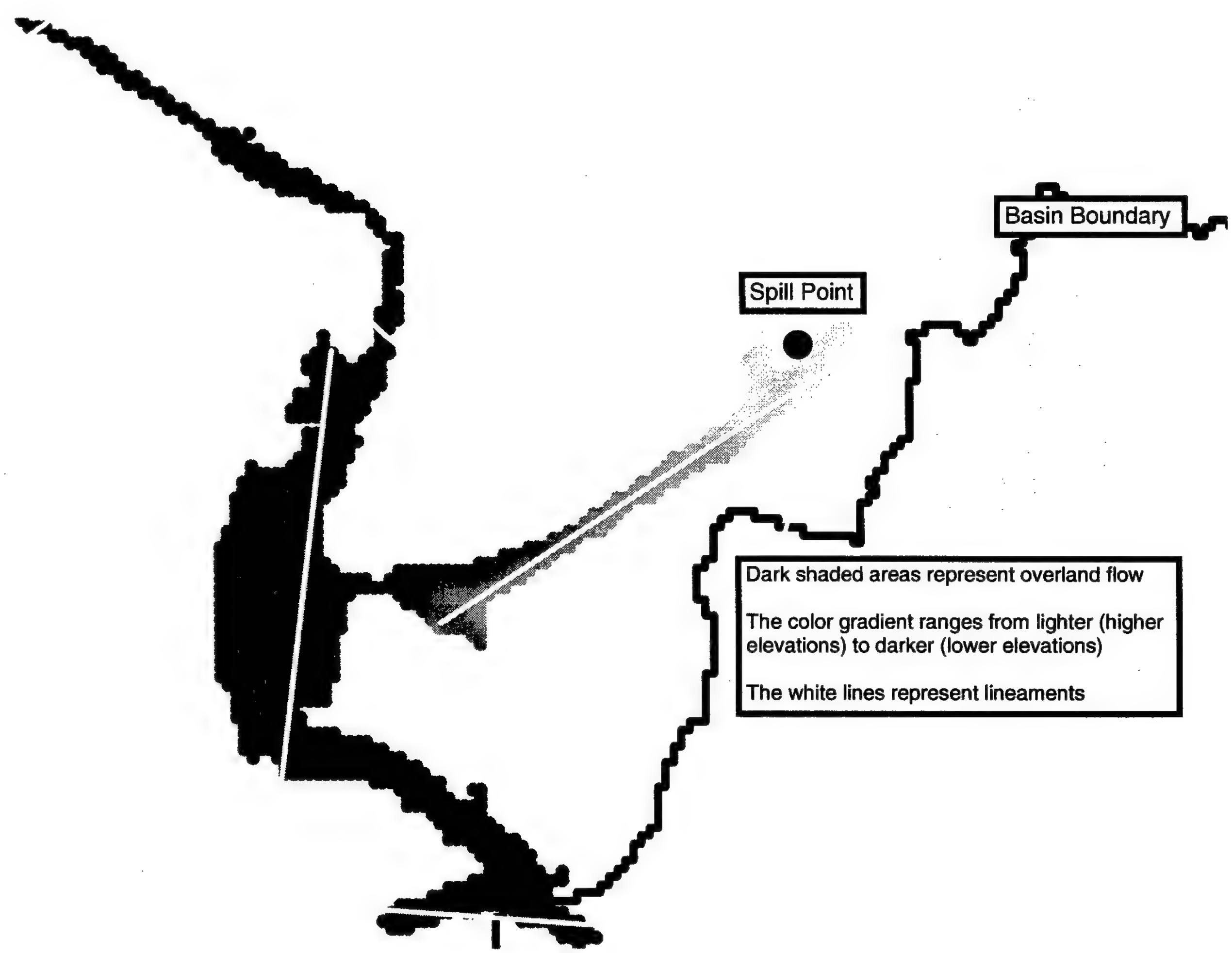


FIG. 24 Sample Run One at Savoy Experimental Watershed Referenced by Clear Creek Basin Boundary

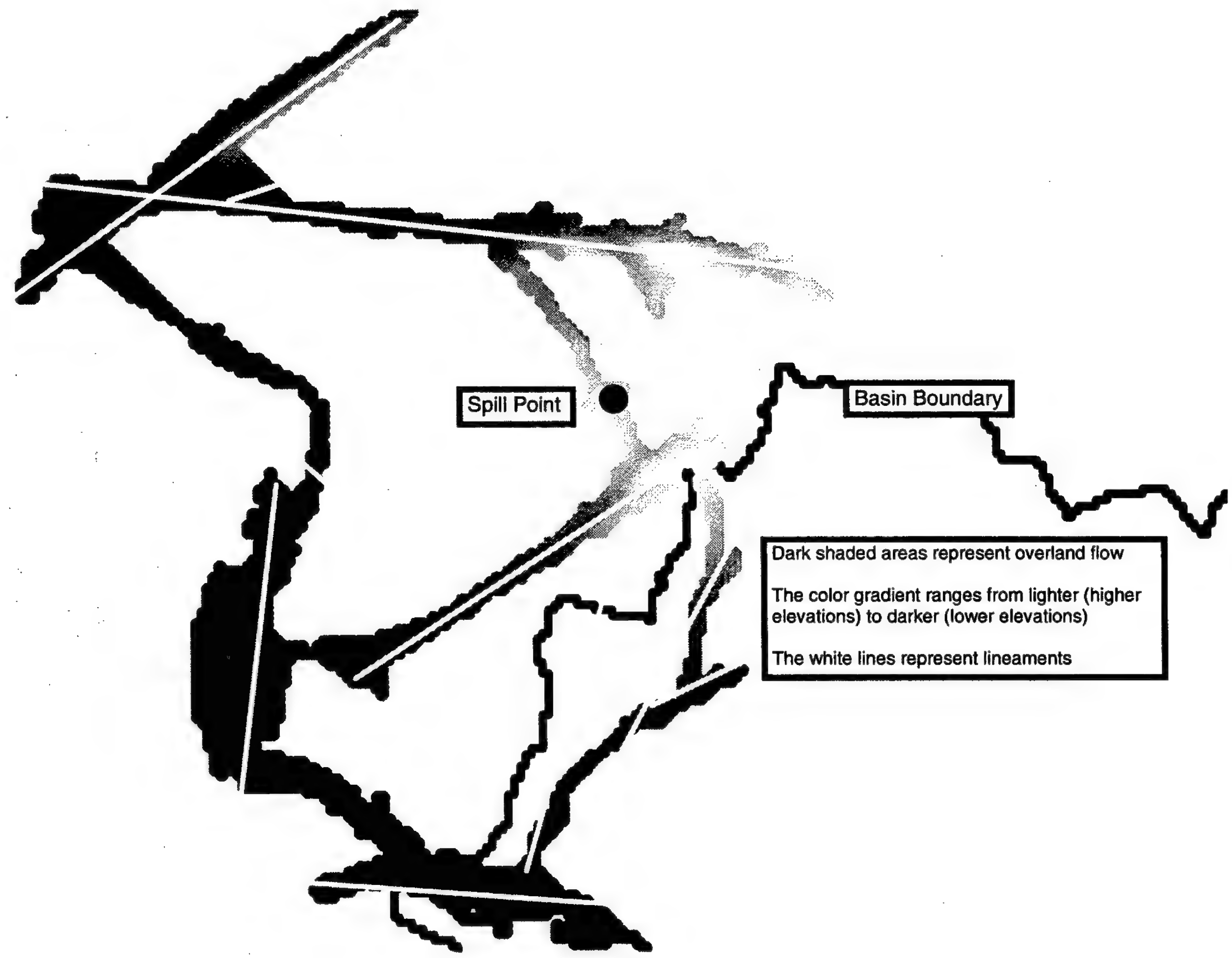


FIG. 25 Sample Run Two at Savoy Experimental Watershed Referenced by Clear Creek Basin Boundary

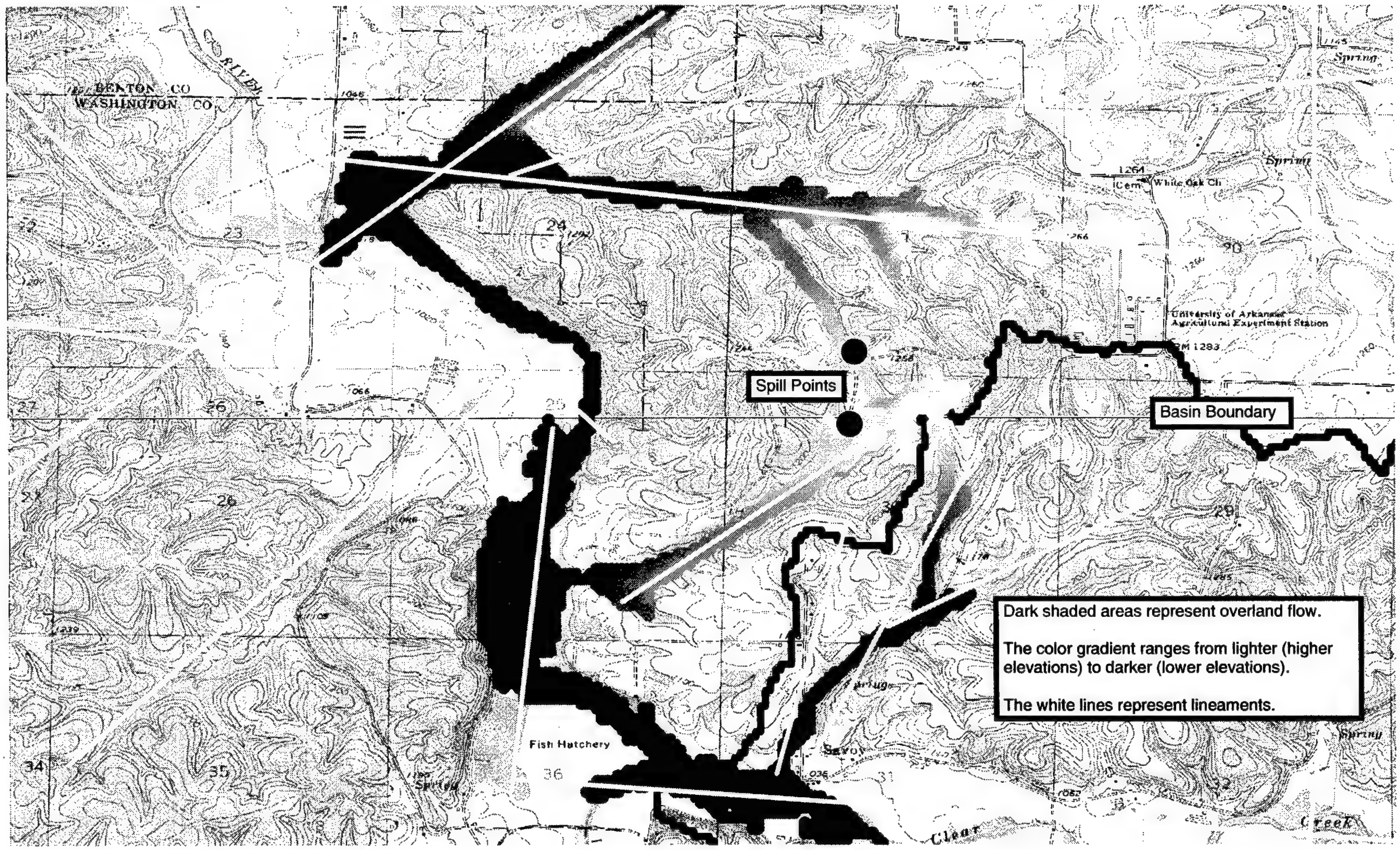


FIG. 26 Sample Run One and Two at Savoy Experimental Watershed Referenced by Clear Creek Basin Boundary

Spillpoint and *Flowdown* Scripts

Johnson

Johnson Spring is located 94.1735 west, 36.1415 north, Springdale, AR, quadrangle. Johnson Spring was contaminated by a fuel spill in 1971 when a fuel truck overturned on Highway 412 (then Highway 68). More than 75,000 trout were killed at the Johnson Spring trout farm, approximately 2 miles southwest from the spill (Johnson and Johnson 2000; "Gasoline Blamed in Fish Kill" 1971). The travel time for the fuel from the spill on Highway 68 to the trout farm was approximately 24 hours. Within 30 minutes of the contaminate reaching the spring at the trout farm the fish were killed. This actual spill would have been an ideal application of the model developed in this dissertation. Had this model been available in 1971, residents in the Johnson Spring area could have been notified and given advance warning of the spill. They could have also been warned of the potential contamination of their water supply.

It is important to note that this dissertation does not address the issue of "who" or "how" the residents would be contacted in the event of a spill. The model produces only a graphical output that shows areas of possible contamination resulting from a spill in a fractured karst area. Users of this model can further manipulate the results by changing the legend type to Graduated Color and the classification field to Grid_code in ArcView. This will allow for variation in color over different elevations for the advective transport flow produced by the model.

The graphics in Fig. 28 - Fig. 37 show different screen views during the model run for the 1971 fuel spill. While the results would be more vivid if they were printed in color, a distinct flow path of is obvious even in black and white (gray scale) print.

The 1971 fuel spill model run shown in Fig. 27 illustrates the possible destinations of contaminants from the spill. The area includes Johnson Spring where the fuel emerged from the spring one day after the accident. Not only does the spring fall within the model output area, but it is also associated with the area having some of the greatest elevation differences. The elevation differences can be seen by the darker shades associated with the model run data (Fig. 27). In Fig.

27, all the area at an elevation lower than the Johnson Spring elevation was eliminated to produce a clearer view of the model data.

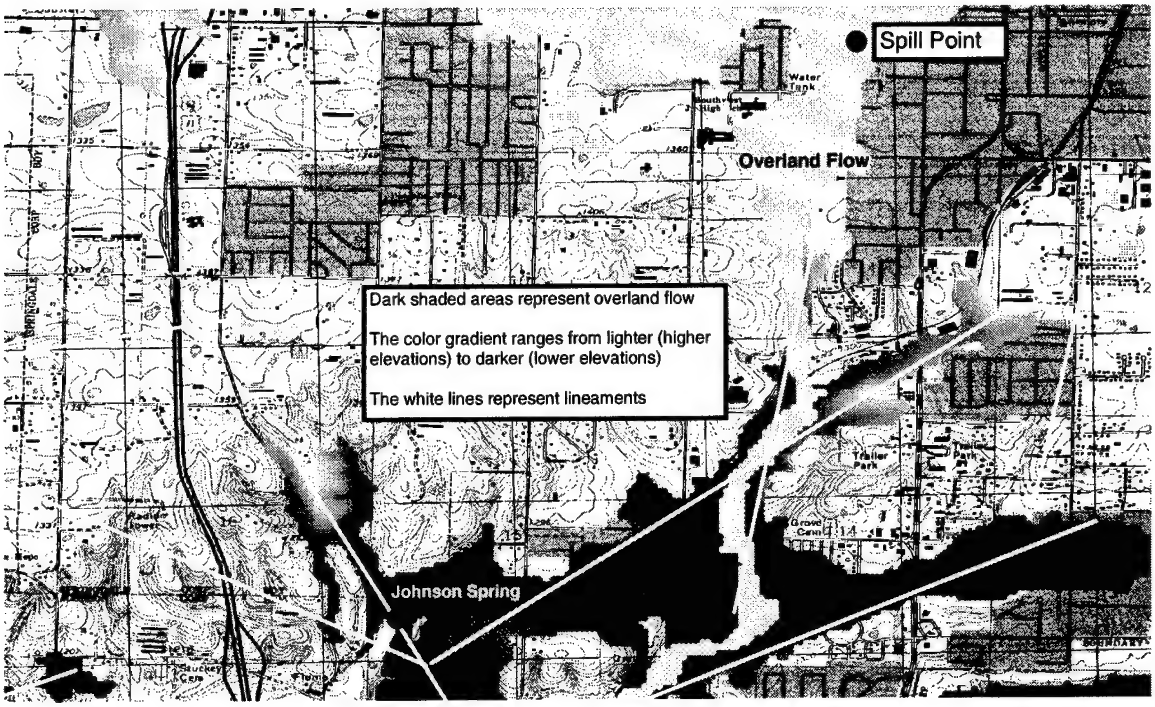


FIG. 27 1971 Fuel Spill Model Associated with Johnson Spring

The topographical map showing the spill site and Johnson Springs can be seen in Fig. 28. The figure is a screen shot in ArcView showing the GeoTiff of the Springdale quadrangle. The graphic in Fig. 29 shows the area (shaded darker) that is located lower than the spill elevation and within the radius set by the user when the model was executed.

The graphic in Fig. 30 shows the DEM for the area around the 1971 spill site. The darker areas represent lower elevations and the lighter areas represent higher elevations.

The graphic in Fig. 31 shows the DEM with the addition of lineaments associated with the area. Many of the lineaments are associated with streams (darker areas) which may be typical for a fractured karst area.

The overland flow associated with the model run, *spillpoint* script, for the 1971 full spill may be seen in Fig. 32. The figure also represents all elevations less than or equal to the spill point elevation within the designated radius and is show as a circular dark area. The lineaments in the area are represented as straight black lines.

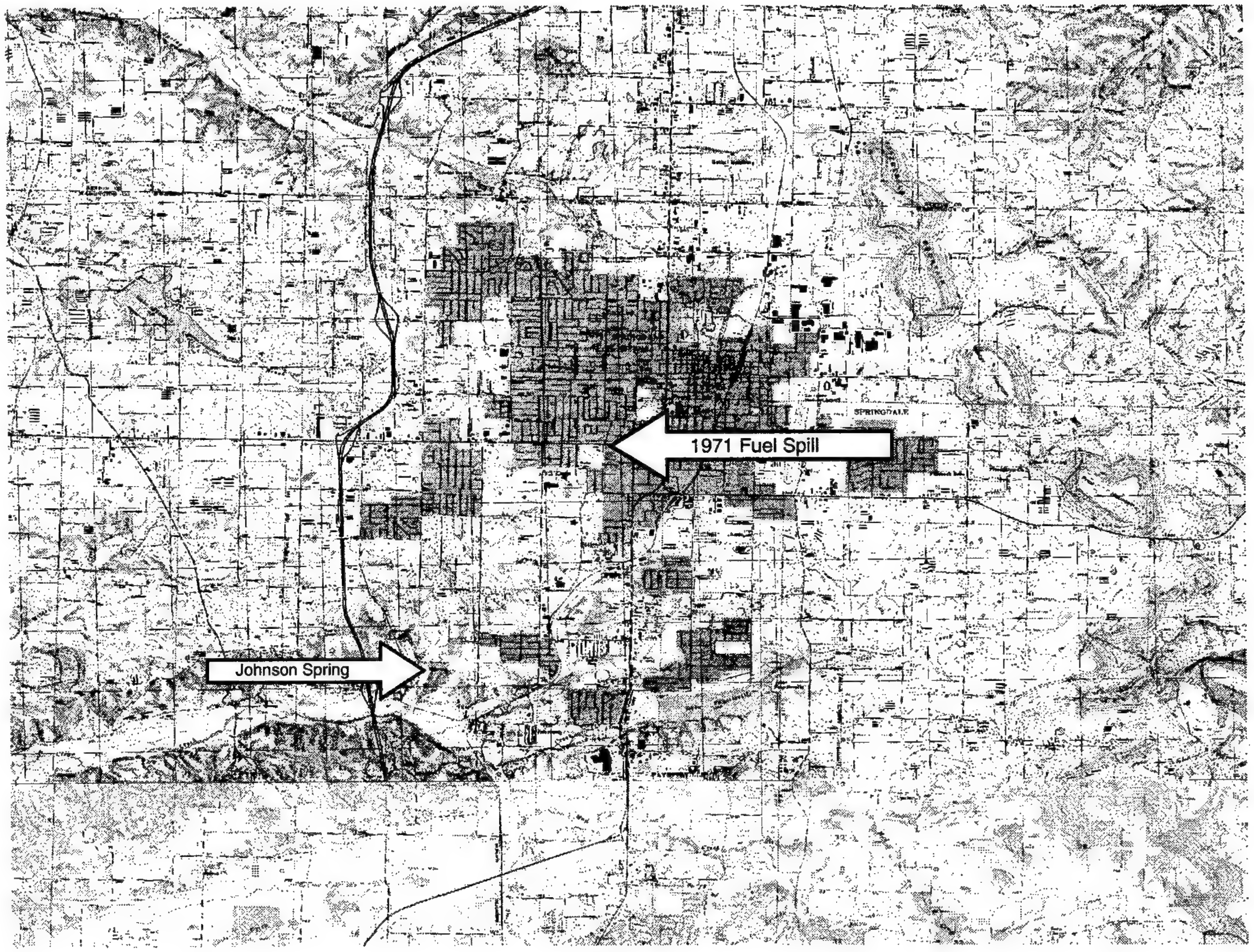


FIG. 28 Springdale, Arkansas, Including Johnson Springs and the 1971 Full Spill Site.

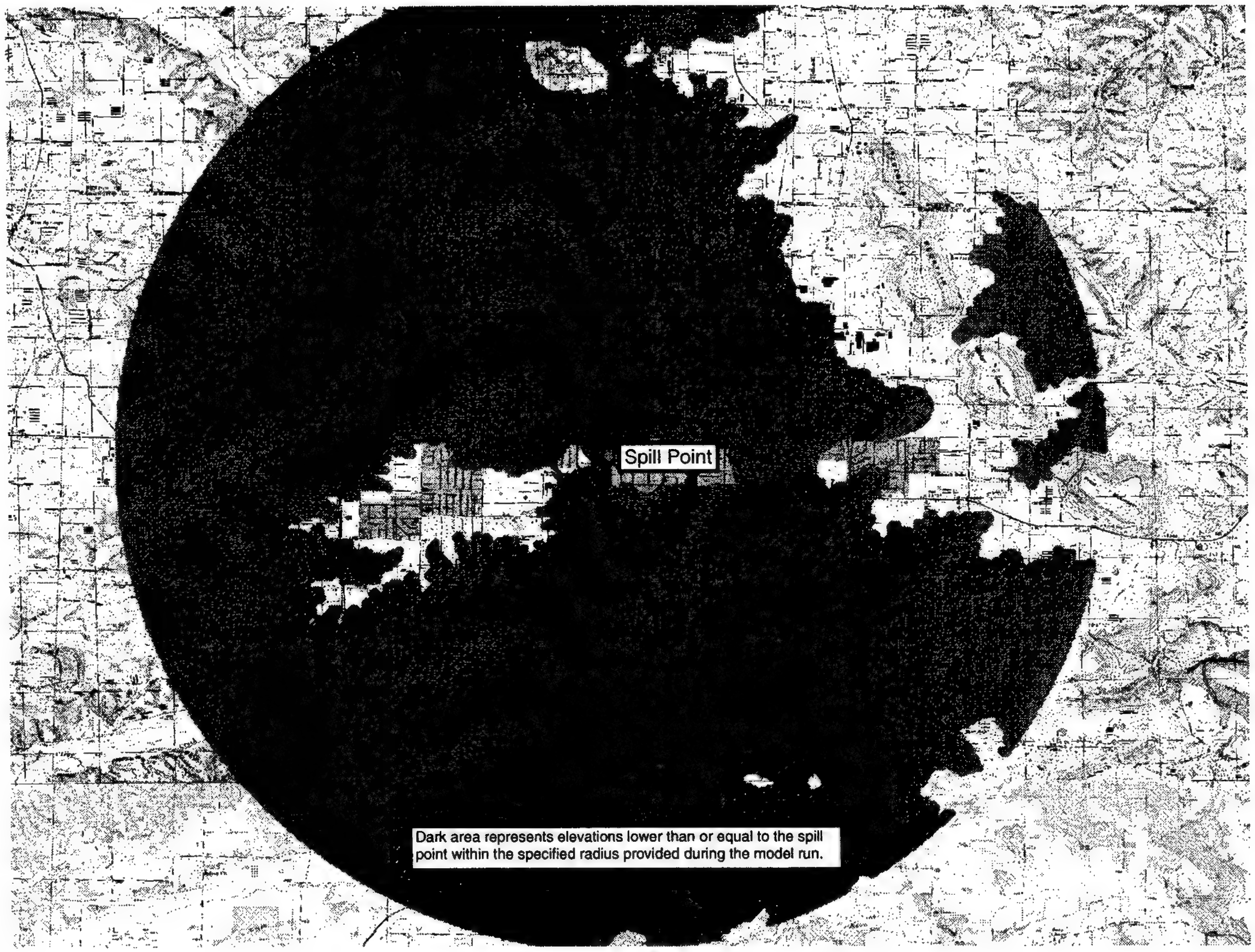


FIG. 29 Area Selected to Model with Elevations Greater Than the Spill Point Removed

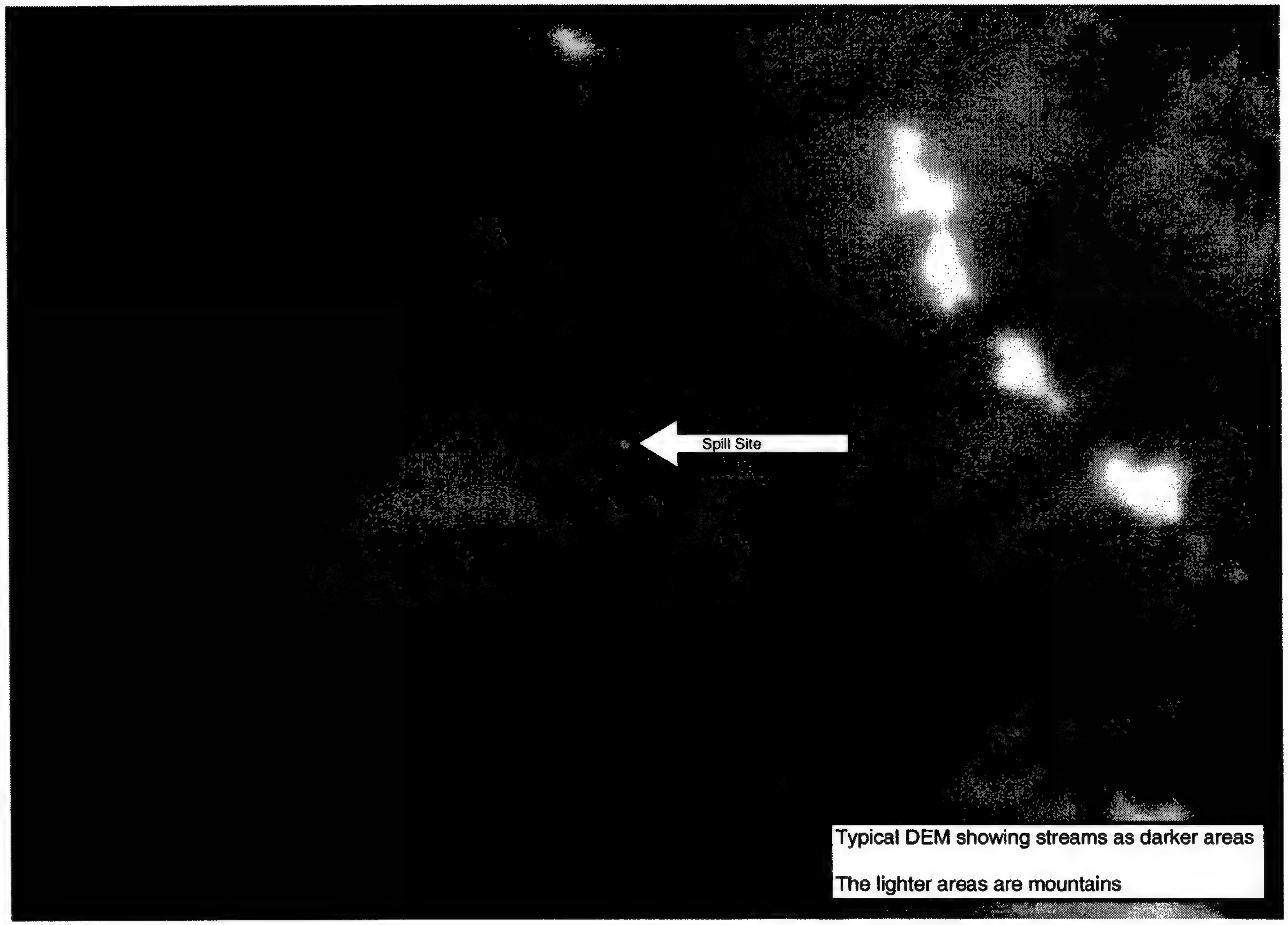


FIG. 30 DEM of the Model Area Including the Spill Point

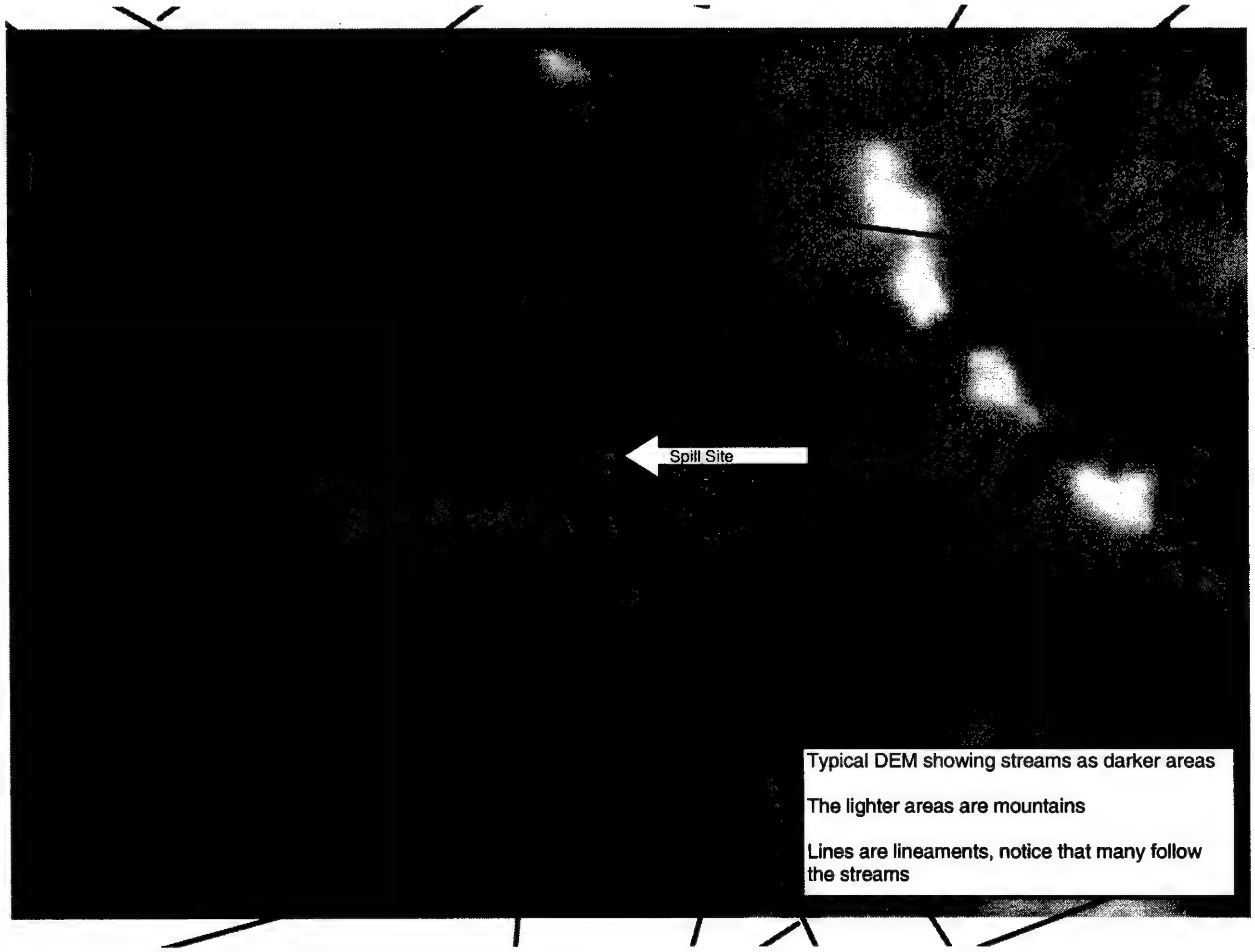


FIG. 31 DEM with Lineaments

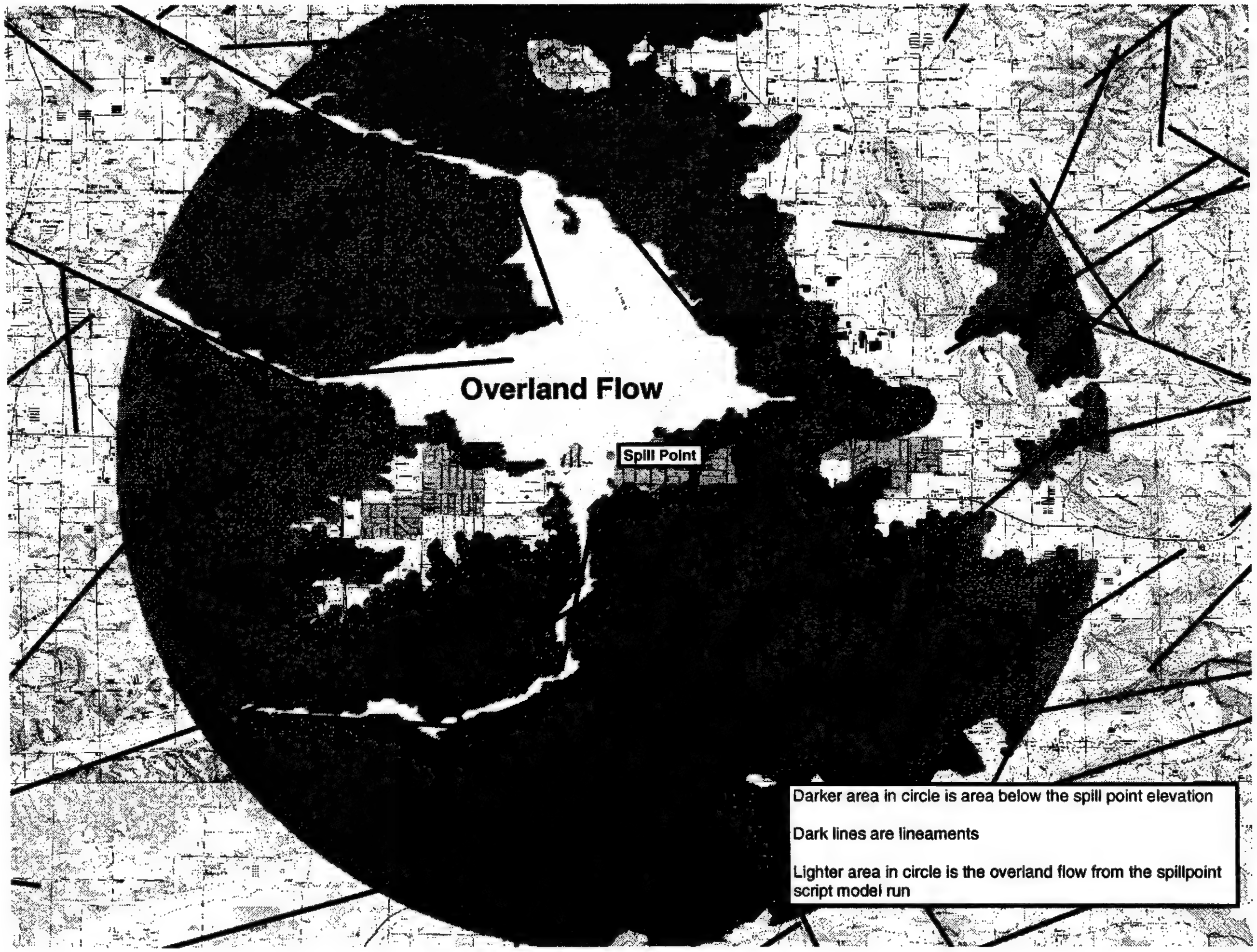


FIG. 32 Johnson Run One

The graphic in Fig. 33 shows the flow from the first run of *flowdown* using selected points that were associated with lineaments that were near the overland flow path created by the *spill-point* script run. The figure only includes areas that were selected during the first *flowdown* run.

The graphic in Fig. 34 is the second run of the *flowdown* script and includes lineaments that the first run of *flowdown* crossed. The graphic has been modified to show only the new areas associated with the second run of *flowdown*.

The graphic in Fig. 35 shows the three flow data layers combined. They include the overland flow using the spillpoint script, run one and run two of the *flowdown* script. In the text version (gray scale) the three layers may be difficult to tell apart.

The graphic in Fig. 36 shows the spill point and spring associated with the advective transport flow produced by the model. Notice that the spill and the spring are in separate sub-basins. This shows that the model and actual spill were associated with interbasin transport, which is typical in karst terrains.

The graphic in Fig. 37 shows the results for the entire area modeled using the 1971 fuel spill. Shaded areas would be the areas of concern for possible contamination.

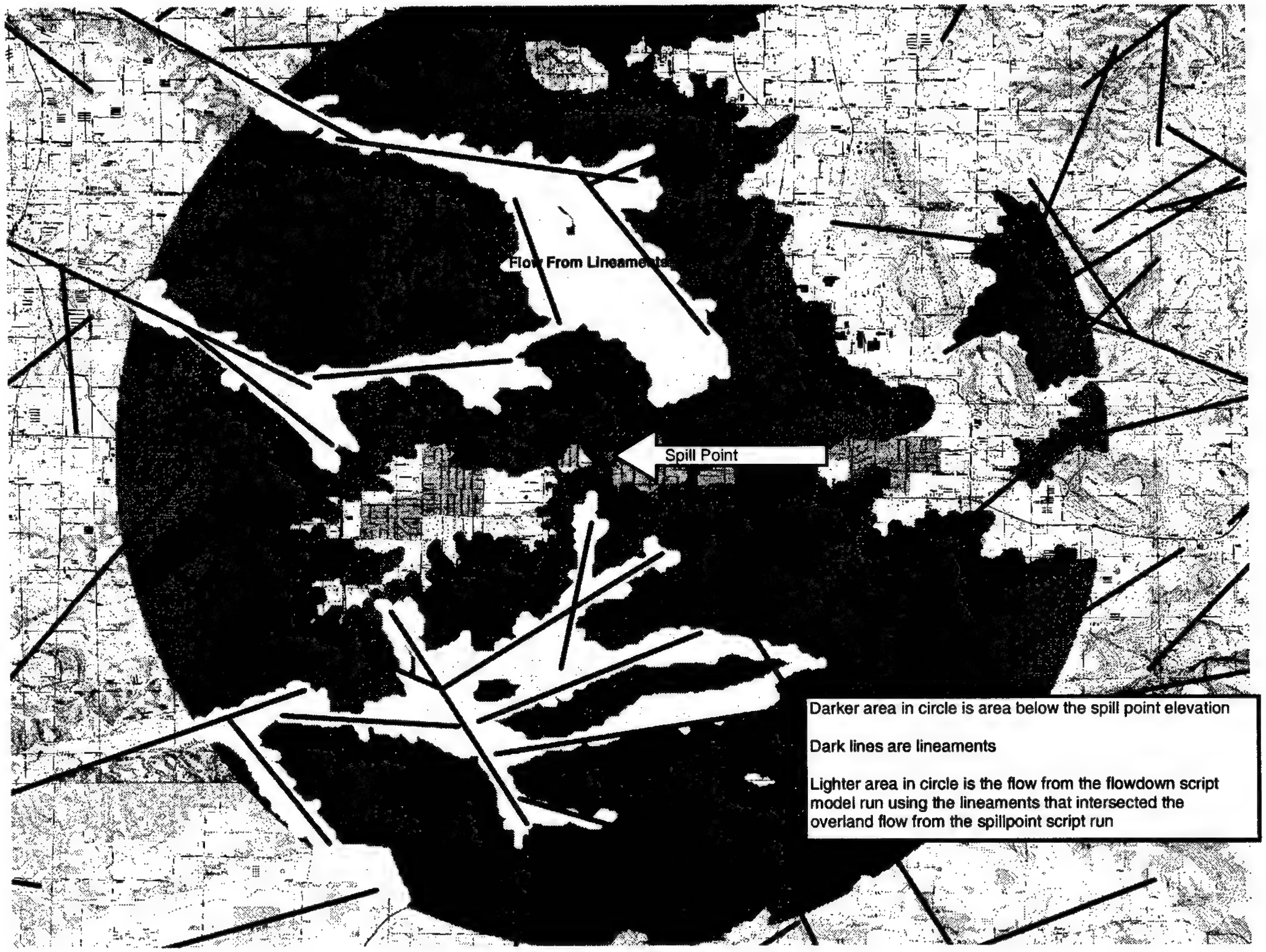


FIG. 33 Johnson Run Two

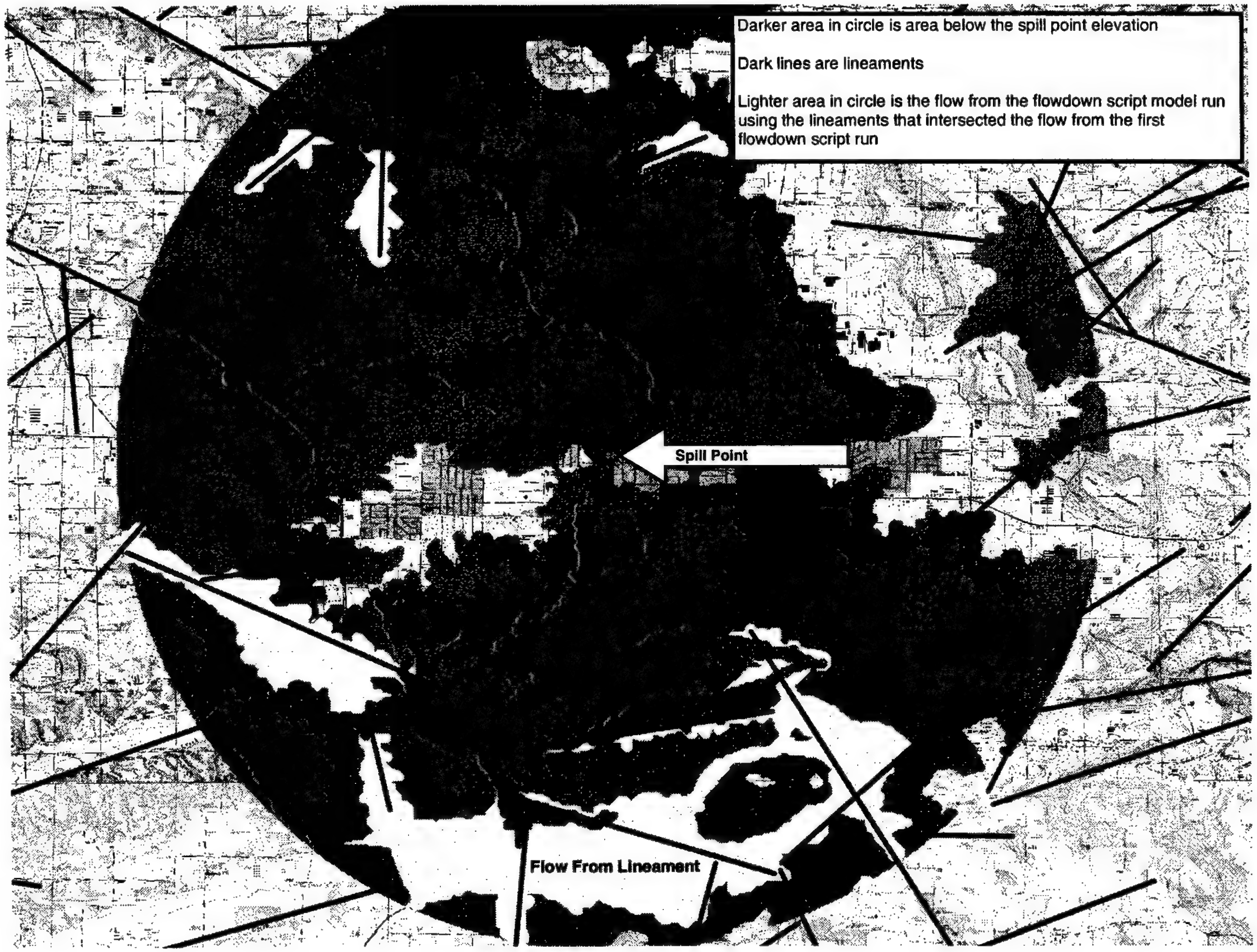


FIG. 34 Johnson Run Three, New Points Only

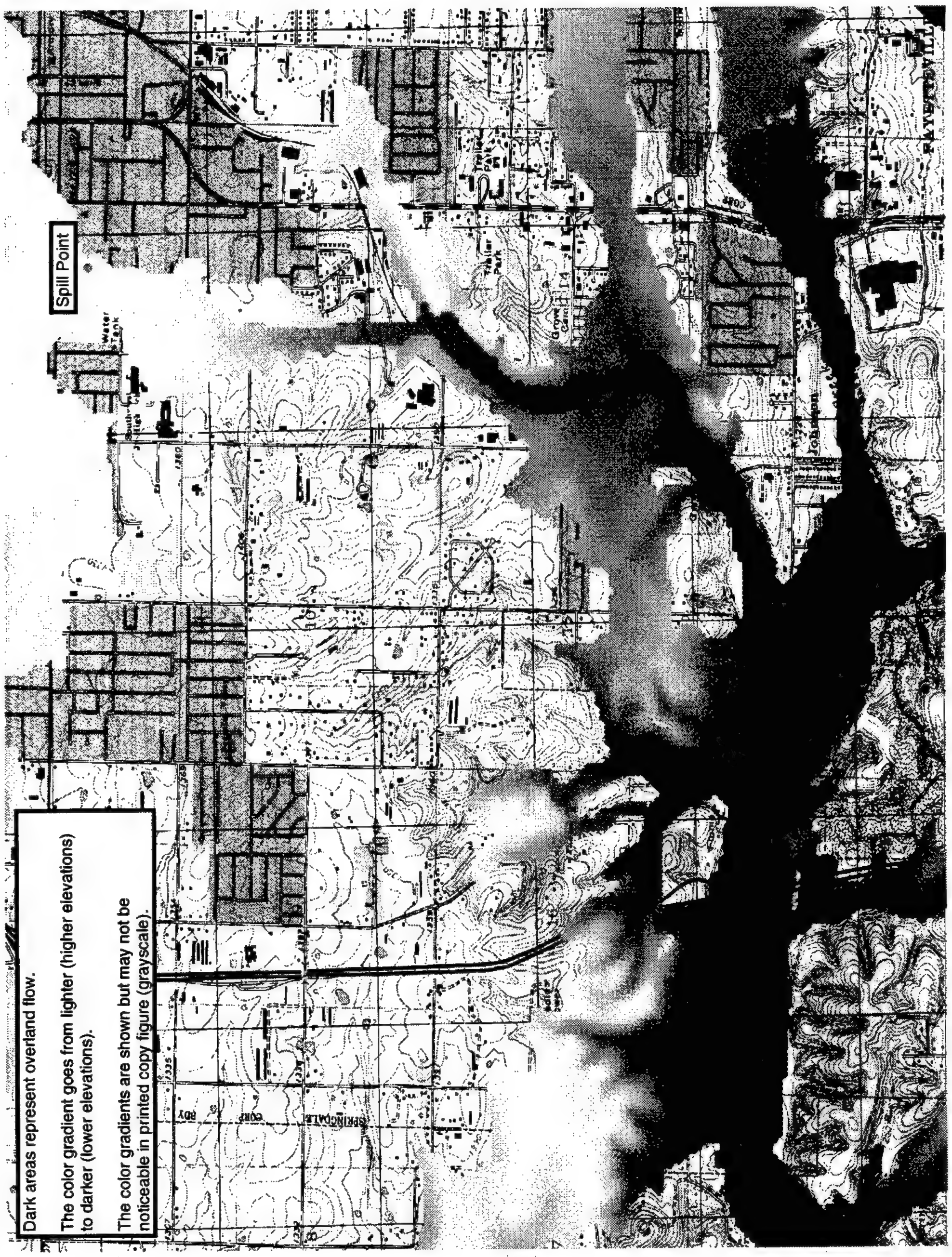


FIG. 35 Closer View of Model Runs

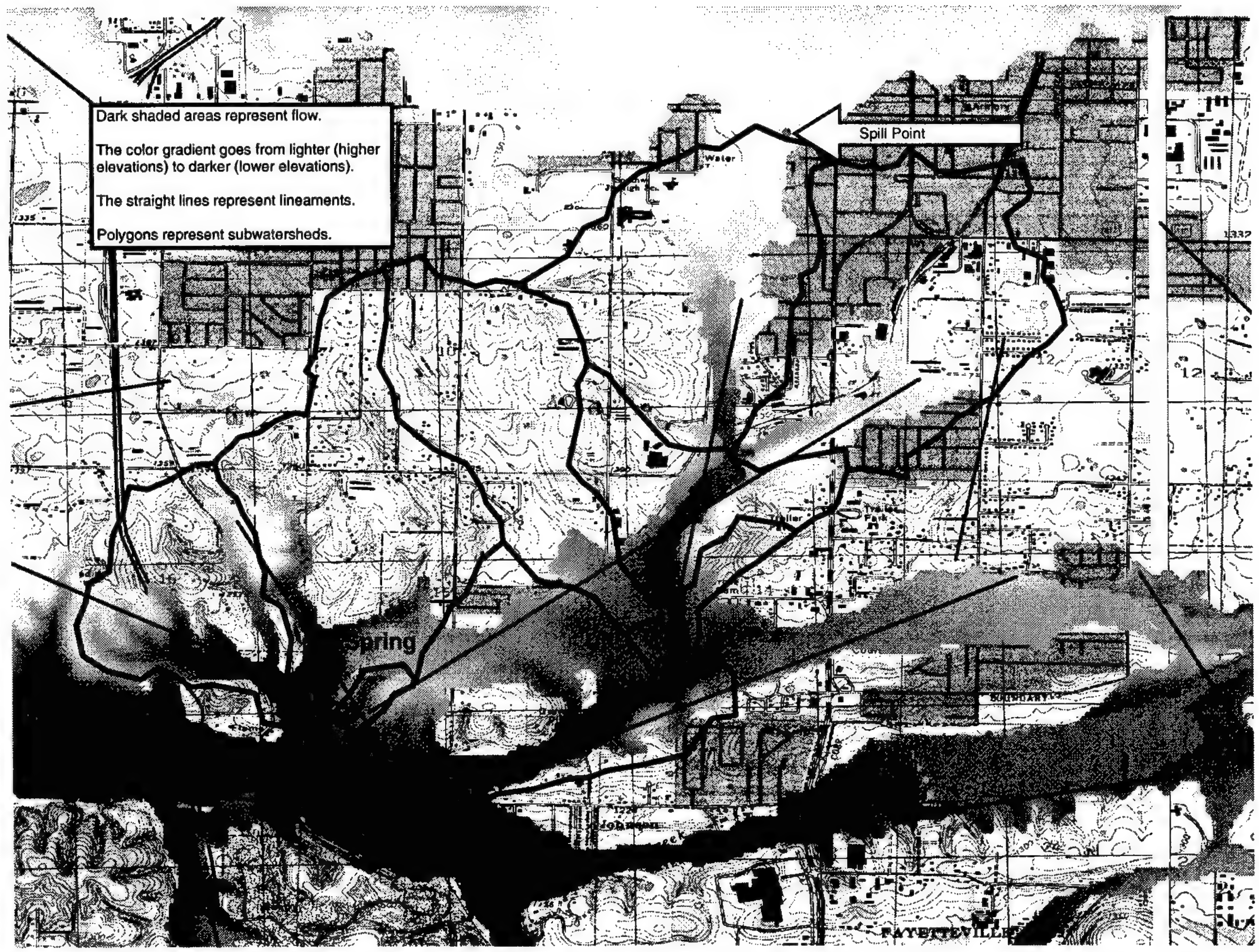


FIG. 36 Model Run Showing Small Watersheds in the Area

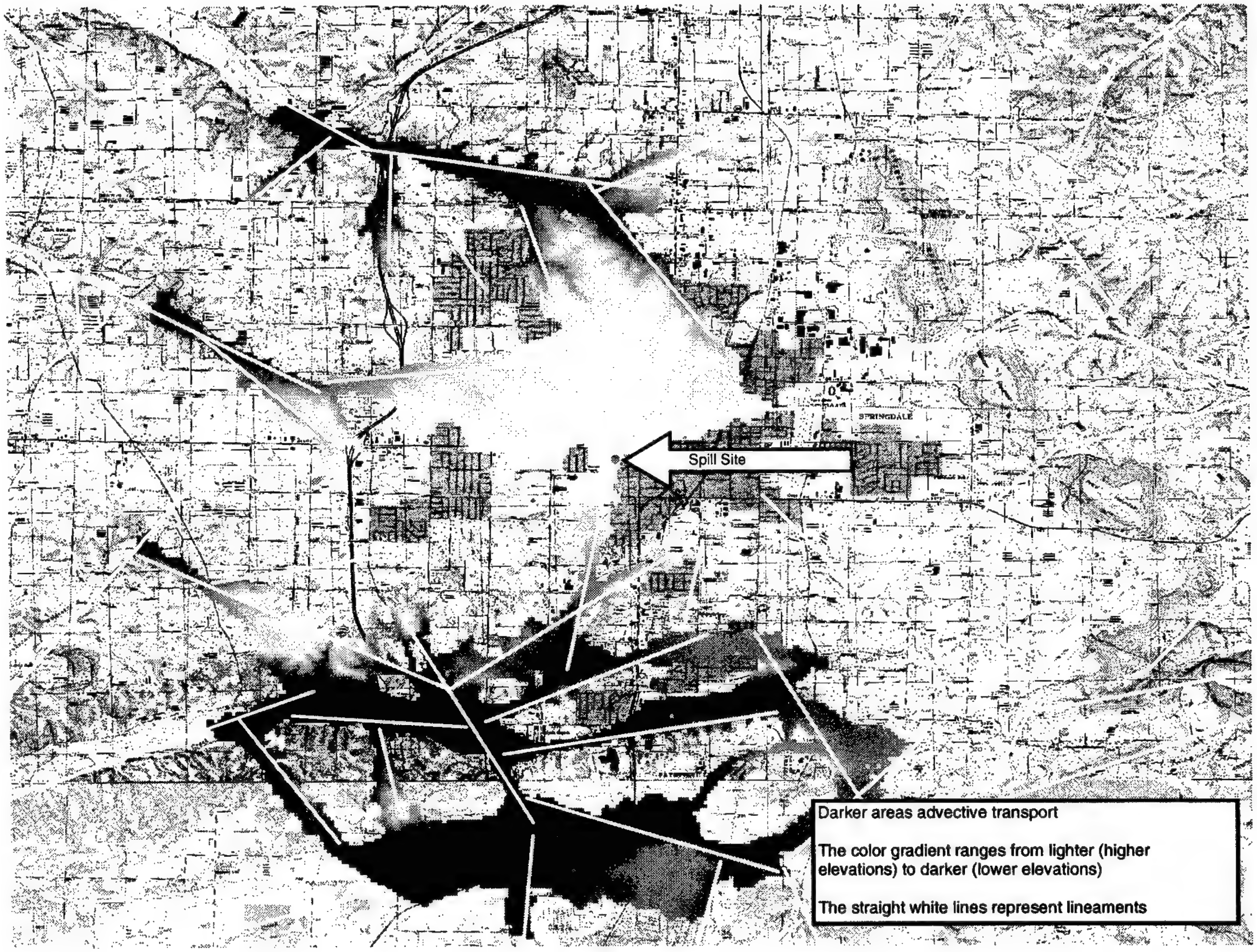


FIG. 37 Model Showing All Locations of Advective Transport Within the Selected Area

Logan Spring

Logan Spring (94.3918 west, 36.1971 north, Gallatin AR quadrangle) has had two dye traces performed (Aley and Aley 1986; Parker and Williams 1992). Two injection sites were used by Parker and Williams (1992) and were selected as the spill sites for the model runs (Fig. 38). The graphics in Fig. 39 - Fig. 41 show model runs using both injection sites using *spillpoint* and *flowdown* scripts. The dye injection locations were in Palmer Hollow (dye injection #1) and Galey Hollow (dye injection #2) (Fig. 38).

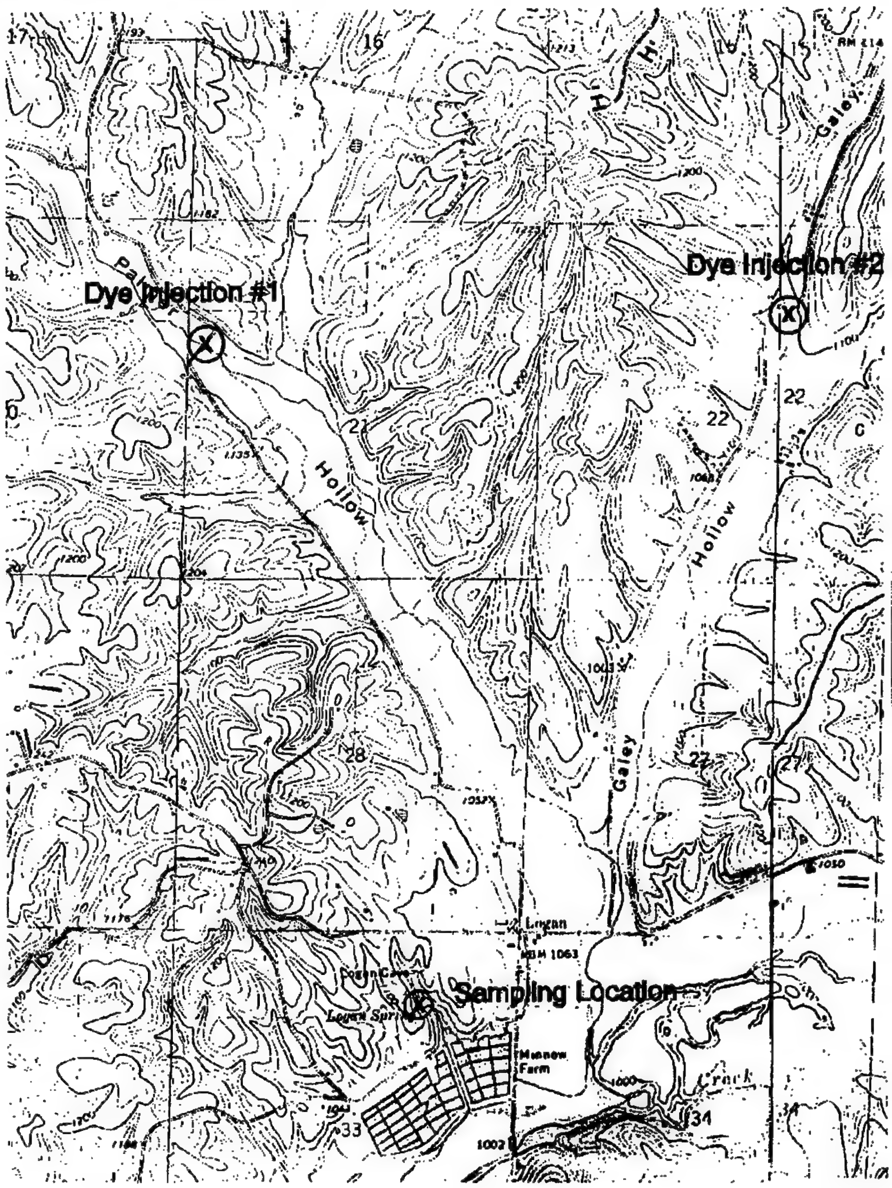


FIG. 38 Location Map from Parker and Williams (1992)

Logan Spring and the combined model runs from both dye injection locations can be seen in Fig. 41. Parker and Williams (1992) and the Aley (1986) results show a strong positive result from the Palmer Hollow injection and a weakly positive result from the Galey Hollow injection site.

The Palmer Hollow and Galey Hollow model runs show that Logan Spring would receive the dye from the injection site. Visual model results illustrate that Palmer Hollow appears to have a more direct access to Logan Spring than the Galey Hollow model run. The Galey Hollow model run must either go under the Palmer Hollow stream or migrate up Palmer Hollow and follow the elevation contour shown in Fig. 41. Even though the actual travel route is unknown, the model results still accurately predict that the dye would reach the spring from both injection sites.

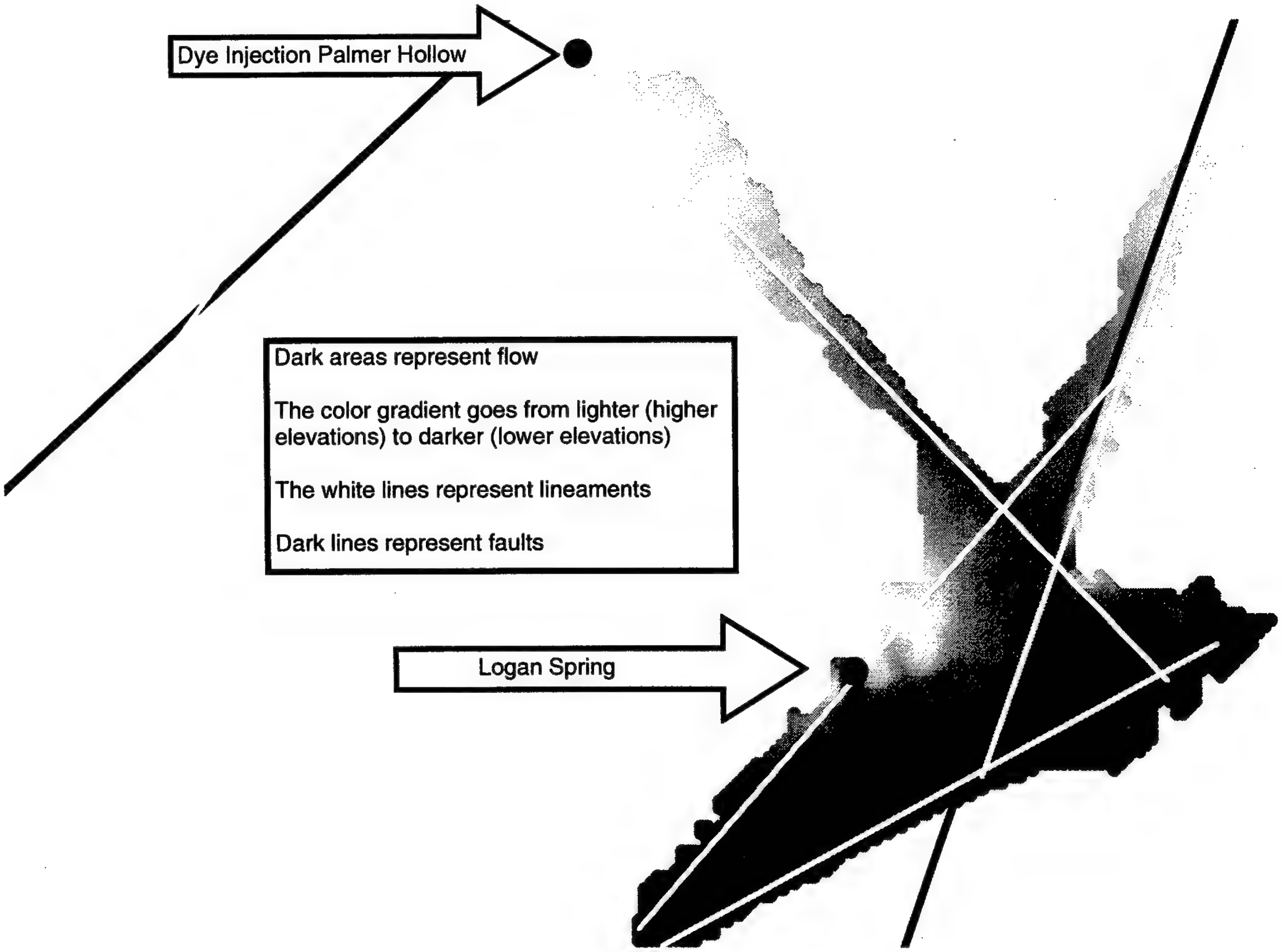


FIG. 39 Logan Spring Dye Injection Palmer Hollow

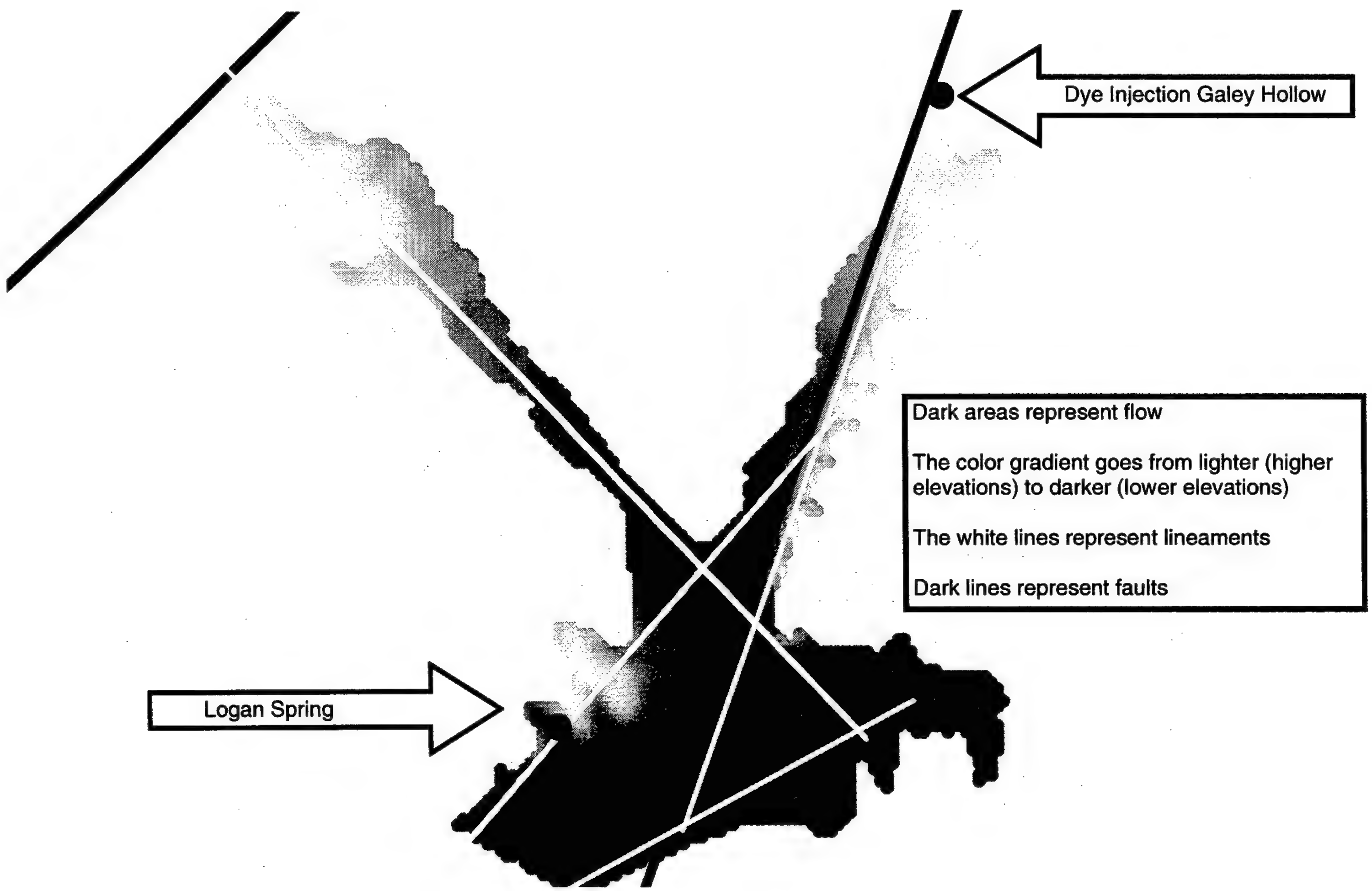


FIG. 40 Logan Spring Dye Injection Galey Hollow

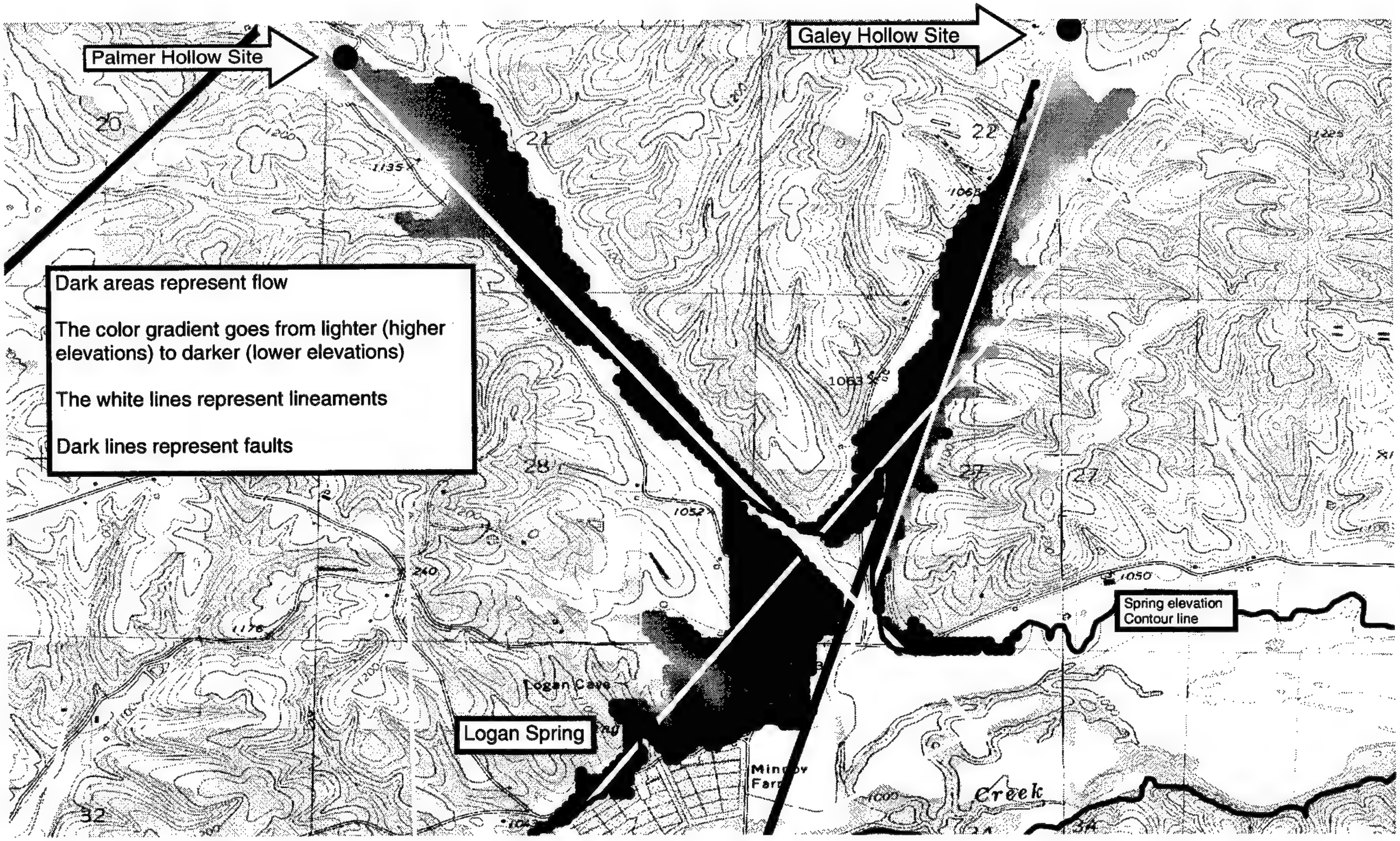


FIG. 41 Logan Spring with Both Dye Injections with Elevations Below Logan Spring Removed

Flowup Script

The *flowup* script was designed to be used in conjunction with the *makeshape* script. The *makeshape* script creates the shape file that is run with the *flowup* script. The *flowup* script should only be used by experienced karst hydrologists. Several things should be considered when using the *flowup* script, including the extent (length) of lineament(s) to be used, surrounding springs, geology and follow-up of areas that may need to be excluded from the springshed produced by the model run.

Cave Springs

The model run for Cave Springs was used to compare the results of this model with two former actual springshed studies (Aley 1978; Williams 1991) which delineated the recharge area, as illustrated in Fig. 42 showing Aley's and Williams's recharge boundaries. Cave Springs (94.3918 west, 36.1971 north, Bentonville South quadrangle) has been studied extensively and has been the center of several environmental concerns. The graphics in Fig. 42 - Fig. 44 show the model run of Cave Springs using the *flowup* script. In Fig. 43 the graphic shows where only a portion of a lineament was used because of the surrounding springs adjacent to the lineament and the downward topography trend. The model assumes that the lineaments act a conduits and those conduits may act as drains. Lineaments associated with springs in areas that show a defined downward slope in topography to the surrounding springs may need to be trimmed to ensure proper placement of the springshed. Documentation for each lineament that is trimmed should be included with the model results and include the reason(s) it was trimmed to eliminate possible bias in the model run. This would also ensure that when others are reviewing the model results, they know the methodology used in the creation of the springshed. In the case of Cave Springs, a new lineament shape line file was created and the lineaments that were intended to be used in the Cave Springs model run were re-created in that shape file and used as the lineament file for the run. Small arrows in Fig. 42 show where parts of lineaments were excluded from the model run because of springs in the area and the topography associated with the lineaments.

As seen in the Cave Springs run (Fig. 42), the model produced an area about twice the size of Aley and Williams springshed delineation. The shaded area is the springshed produced by the model. Also, Fig. 44 shows an area that was deleted from the springshed area because of the possible draining effect of the lineaments in that area. The results indicate that the springshed could be larger than previously documented by Aley and Williams. Both the new area to the north-east and the area removed from the model data would be excellent areas to perform dye tests in the future. The results of the *flowup* model should be used as a screening tool for future dye testing to verify the extent of the springshed.

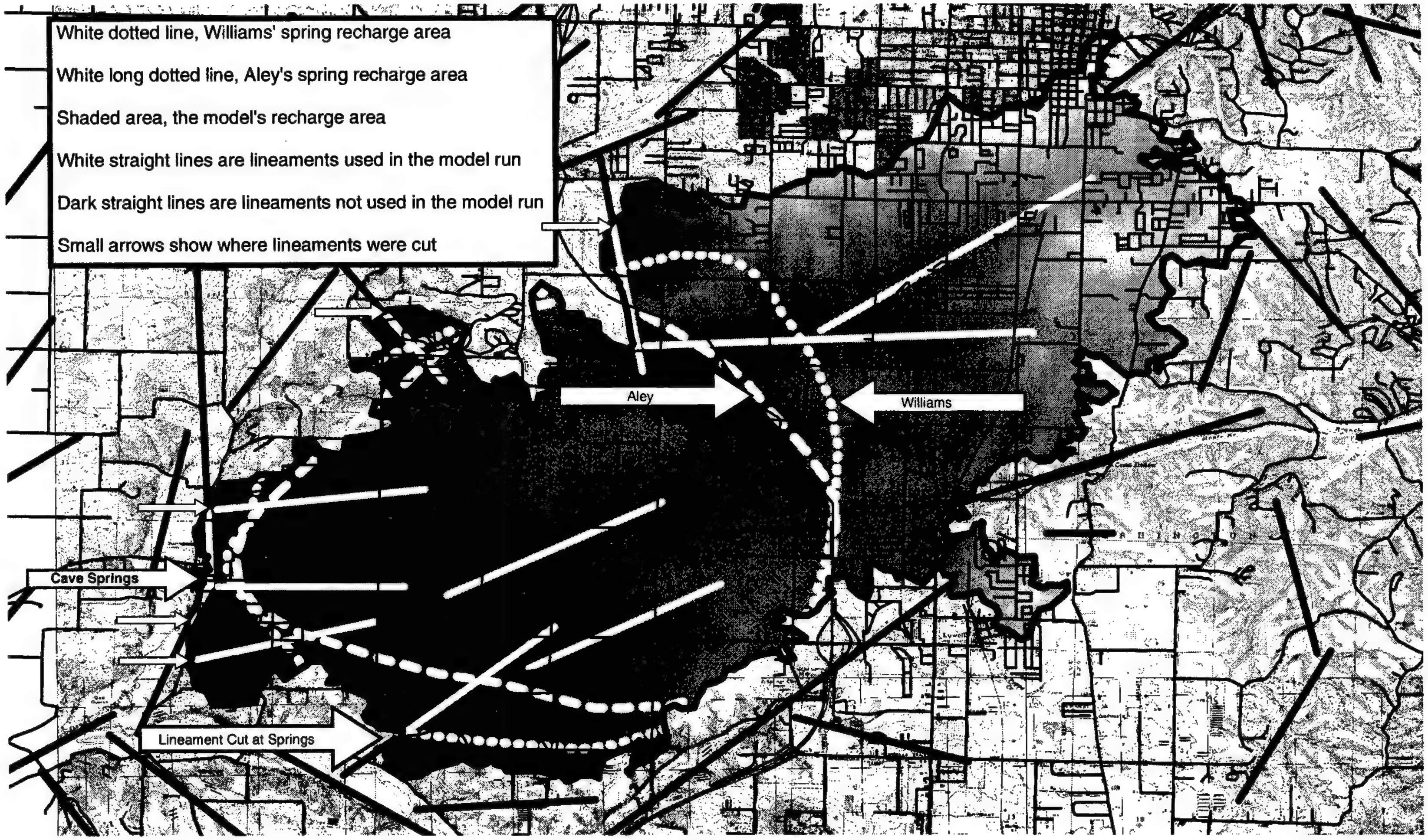


FIG. 42 Cave Springs Showing Aley and Williams Springshed with a Springshed (Flowup) Model Run

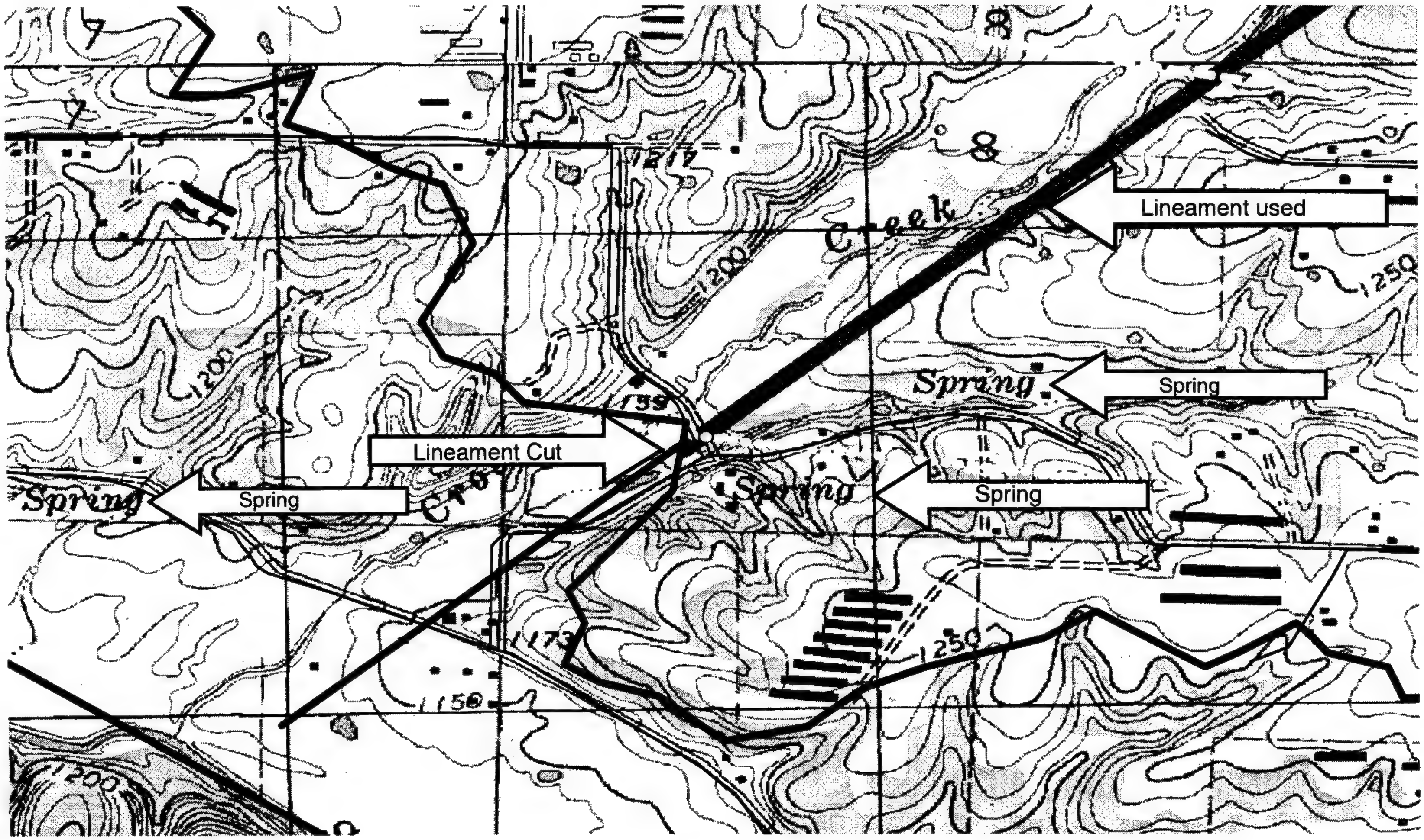


FIG. 43 Cave Springs Model Run Showing Lower Left Corner with Lineament Cut

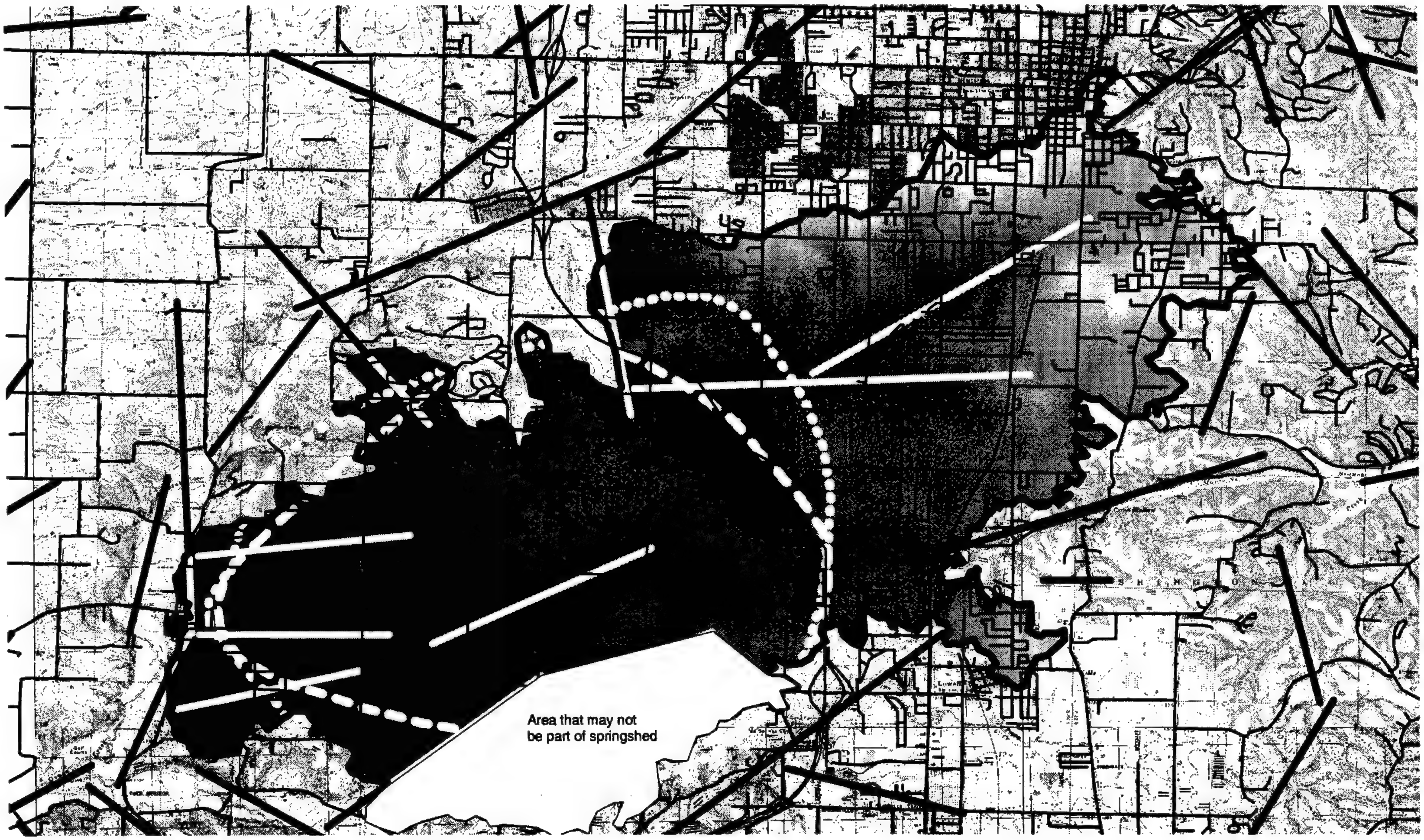


FIG. 44 Cave Springs Model Run with Possible Exclusion Area

Stroud Spring

Stroud Spring was selected as a test area because of a previous dye test that had been run at the spring. Stroud Spring (94.1632 west, 36.4528 north, Bentonville North AR quadrangle) includes a run where a new lineament was added and used for modeling with the *flowup* script. The graphic in Fig. 45 shows the results of the model run of Stroud Spring using the *flowup* script. The same concept of creating a new shape file was used in the Stroud Spring model run. Creating new lineament files will eliminate the original lineament file from being corrupted by adding lineaments that are not associated with the original lineament work.

The Stroud Spring model run (Fig. 45) shows a dye injection site and the spring. The model results show that the dye injection site is in the springshed area for Stroud Spring when run with the new lineament. The new lineament was added because no lineament(s) were associated with the spring and the spring has a defined flow and fracture pattern that resembles the orientation of the new lineament. Also, the new lineament is associated with topological features and is parallel to other lineament in the vicinity.

The most thorough lineament studies may miss some lineaments and some areas may not show features that may be remotely sensed. Most springs are associated with fractures or faults that localize the flow. When a spring does not have a lineament associated with the spring's outfall, it may be assumed that a fracture trace is missing from the lineament data. When this is the case, additional research of the spring may be needed to produce the best phantom lineament(s) possible for use with the model.

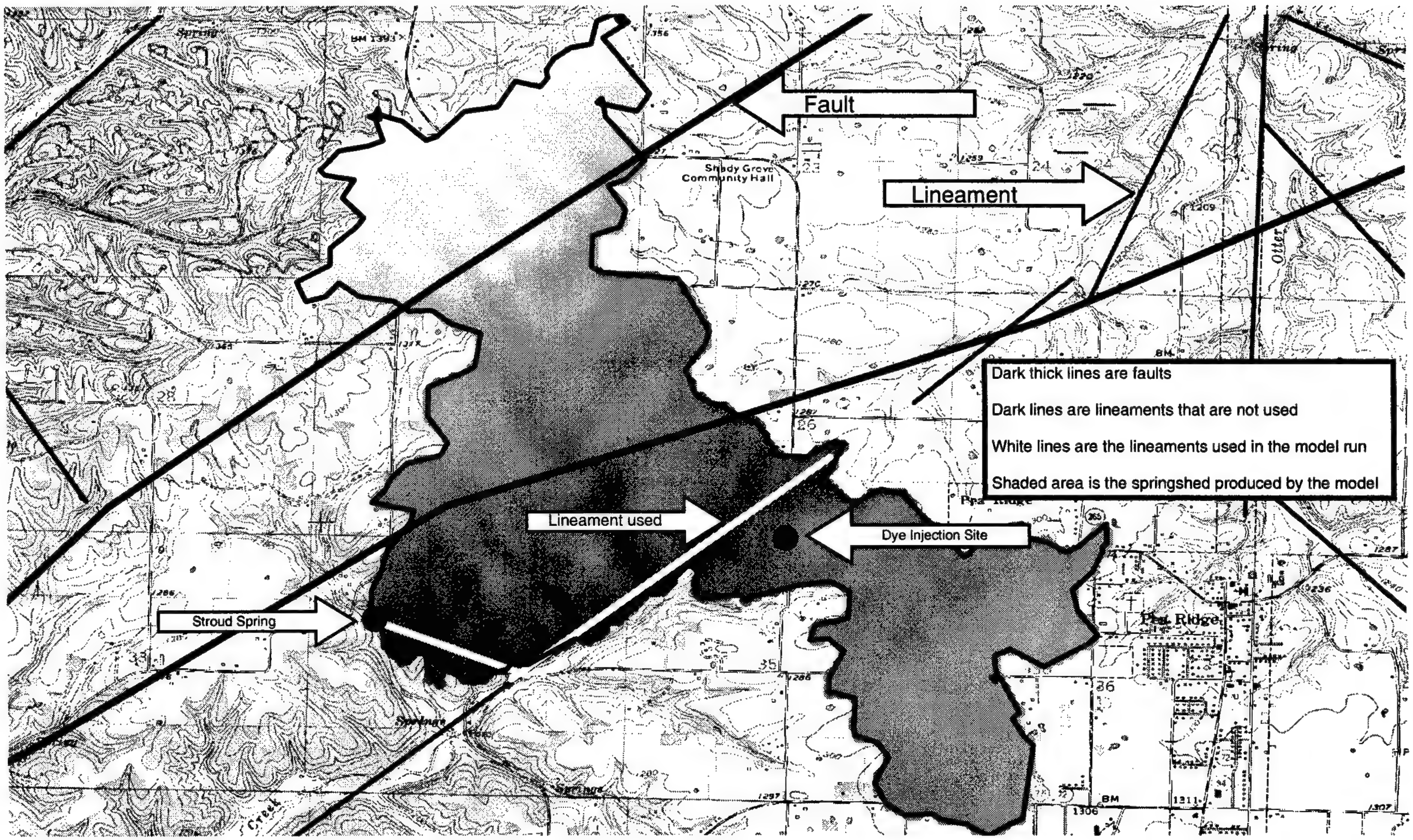


FIG. 45 Stroud Spring Model Run

Decatur Spring

The Decatur Spring was selected because a hand drawn springshed boundary was available for comparison (Brahana and Davis 2000). Decatur Spring (94.4504 west, 36.3557 north, Gentry, AR, quadrangle) shows a simple output of a springshed (Fig. 46). The graphic in Fig. 47 shows the *flowup* script model run along with a hand-drawn springshed for the spring. No lineaments were used in this run because no lineaments crossed the watershed boundary up-gradient from the spring.

The graphic in Fig. 46 shows the model results for the Decatur Spring using the *flowup* script. In Fig. 47, the model's results are illustrated alongside the hand drawn delineation (Brahana and Davis 2000) are shown in Fig. 47. The springsheds produced by hand and the model are very similar. The areas that are not identical are most likely associated with the initial placement of the spring.

Johnson Spring

Johnson Spring is located at 94.1735 west, 36.1415 north, Springdale, AR, quadrangle. The graphic in Fig. 48 shows the output of the Johnson Spring springshed along with surface drainage basins that make up the springshed.

Johnson Spring springshed was run to see what the extent of the recharge area may look like. As expected, the recharge area includes the site of the 1971 fuel spill. The springshed in Fig. 48 is an excellent example of how a separate watershed may be associated with a spring outfall.

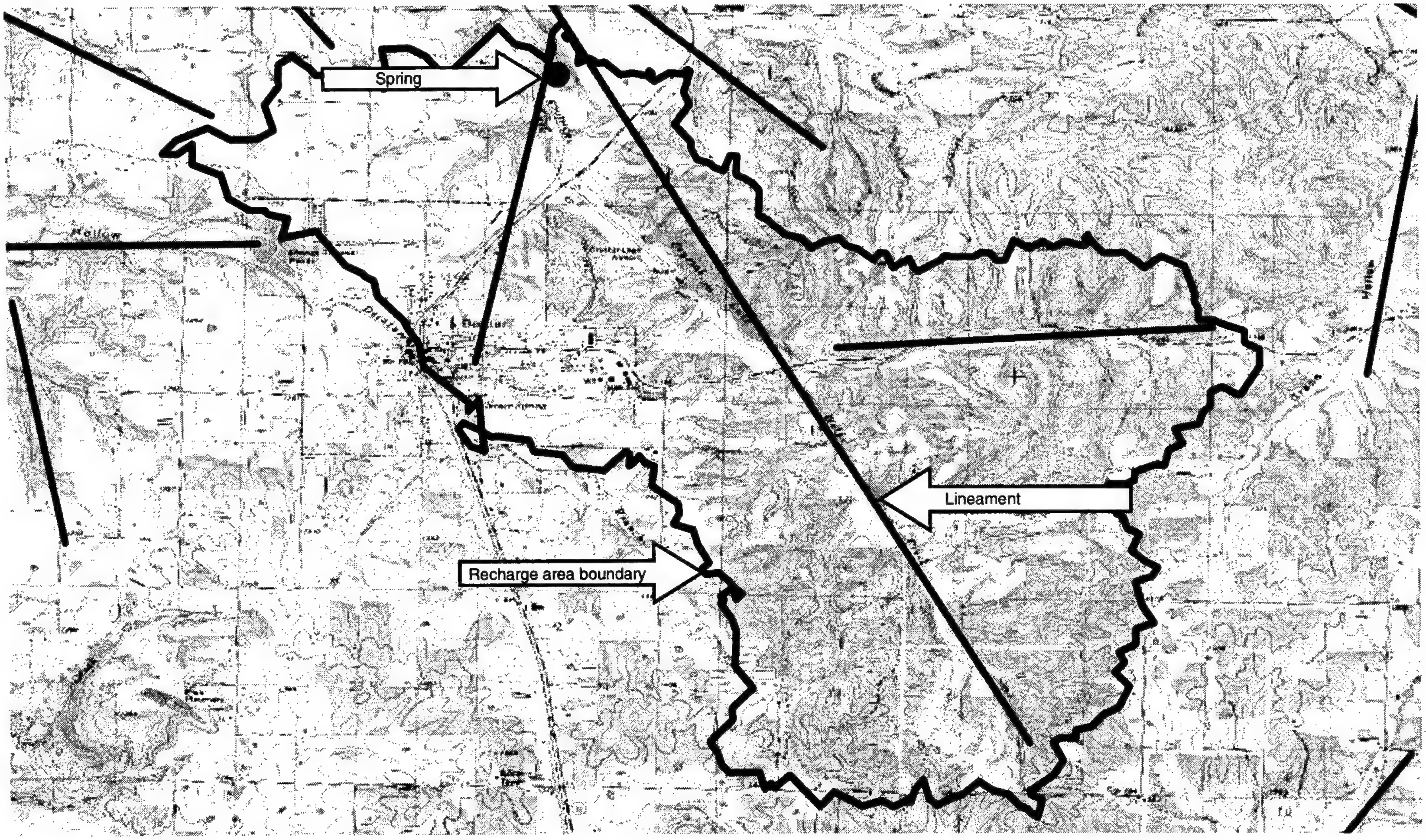


FIG. 46 Decatur Spring's Springshed Using the Model Flowup

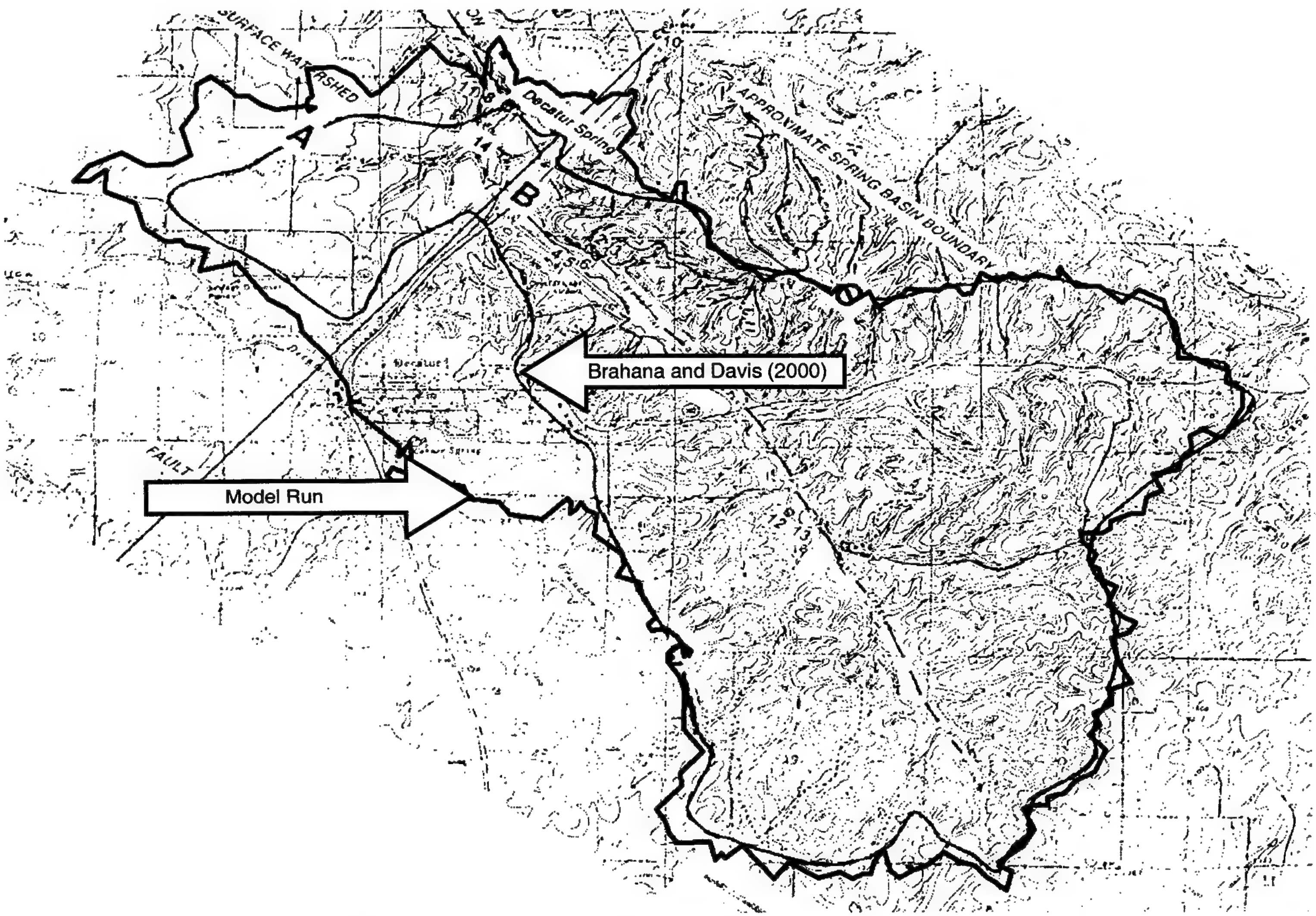


FIG. 47 Decatur Spring with the Model's Results and Dr. Brahana's Results

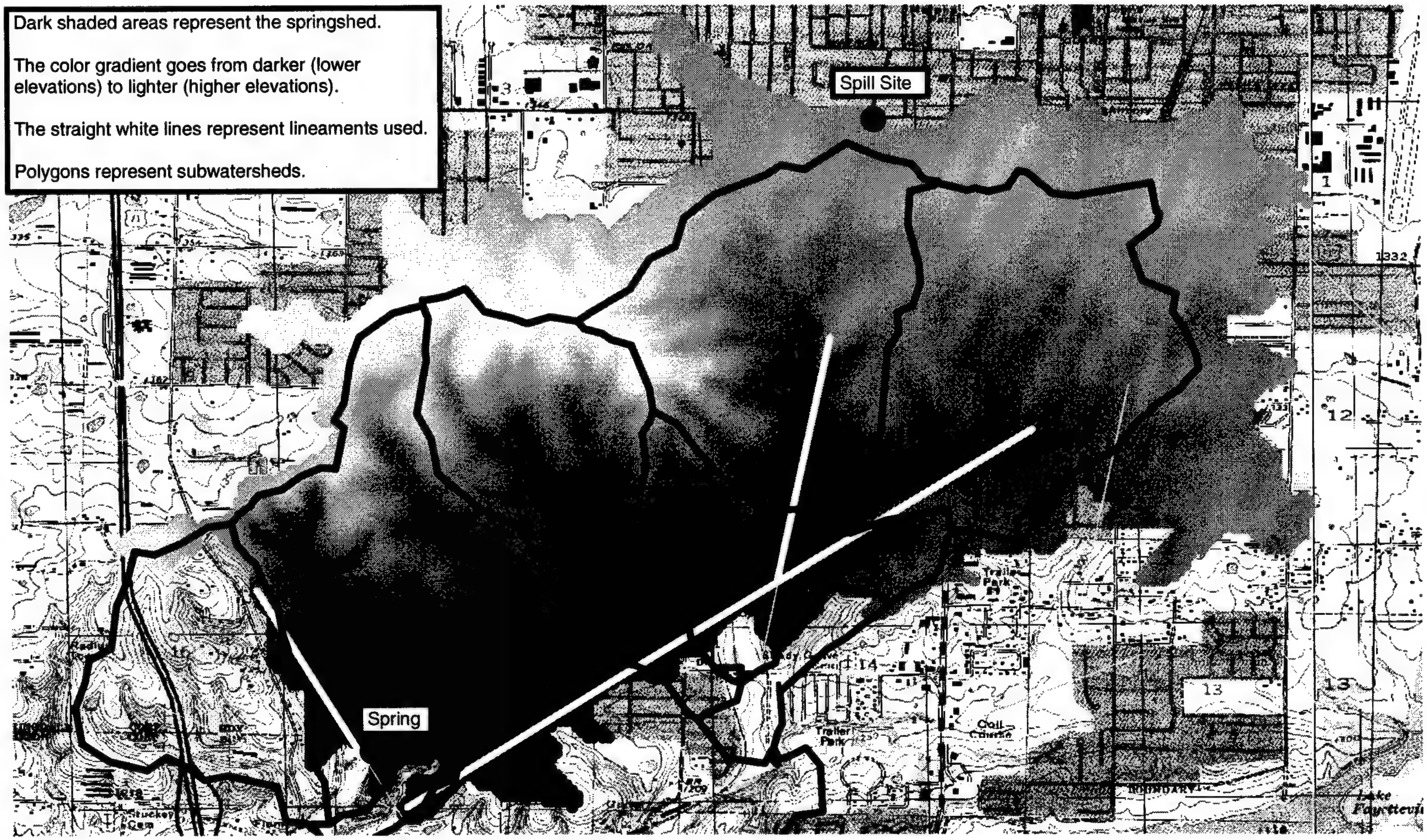


FIG. 48 Johnson Spring Springshed using Lineaments Shown in White

CONCLUSION

The model has been used with only limited data to produce results that mirror real world examples. For example, data collected from the model runs aligned with data collected from actual historical data associated with Johnson Spring and Logan Spring. Thus, the model results compared well with both real-world spill data and dye tracing data provided from the research community. Model runs for the areas of Cave Springs, Stroud Spring, Decatur Spring, and Johnson Spring showed that the flowup script produces results that align favorably with either past springshed evaluations, dye tests or actual spill data.

The model is limited in that it can only be as accurate as the lineament and DEM data available for the area being studied. For example, the last major regional lineament study in Northwest Arkansas was completed in 1973 and could greatly be enhanced by using modern technology for remote sensing. However, with accurate data, the model has the potential to be used to predict possible contamination areas for a spill as well as predict springsheds.

The springshed (*flowup*) script may have the greatest potential for future use. By using it to produce a springshed for screening purposes, it would allow the modeler to review areas that may not have initially been assigned to the spring. This would allow for a more constructive dye test by showing the modeler areas to inject the dye and may possibly help confirm or eliminate areas without the need for dye tracing when used by a karst hydrologist.

The model seems to follow Pareto's Principle in that a small amount of data produces the majority of the desired results. If engineers and scientists can accept that this simplistic model's results are worth reviewing and provide further research in this area, this new type of model may be one of the ways fractured mantled karst areas are modeled in the future.

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APPENDIX A

USGS
science for a changing world

National Elevation Dataset

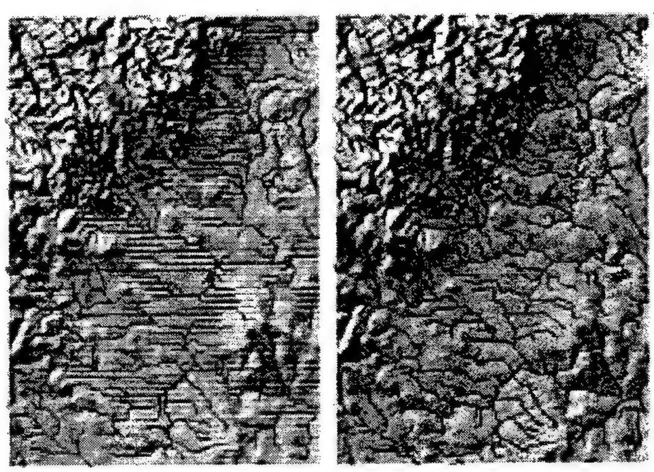
Fact Sheet 148-99 (September 1999)

| Data Characteristics | Metadata | Applications | Obtaining Data | Information |

The National Elevation Dataset (NED) is a new raster product assembled by the U.S. Geological Survey (USGS). The NED is designed to provide national elevation data in a seamless form with a consistent datum, elevation unit, and projection. Data corrections were made in the NED assembly process to minimize artifacts, permit edge matching, and fill sliver areas of missing data.

United States portion of the National Elevation Dataset Figure 1: A shaded-relief representation of the conterminous (NED). Elevation is portrayed as of range of colors, from dark green for low elevations to white for high elevations.

Data Characteristics



The NED has a resolution of 1 arc-second (approximately 30 meters) for the conterminous United States, Hawaii, and Puerto Rico and a resolution of 2 arc-seconds for Alaska. National Elevation Dataset data sources have a variety of elevation units, horizontal datums, and map projections. In the NED assembly process, the elevation values are converted to decimal meters as a consistent unit of measure, North American Datum 1983 is consistently used as horizontal datum, and all the data are recast in a geographic projection. Older digital elevation mod-

els (DEM) produced by methods that are now obsolete have been filtered during the NED assembly process to minimize artifacts that are commonly found in data produced by these methods. Artifact removal greatly improves the quality of the slope, shaded-relief, and synthetic drainage information that can be derived from the elevation data. Figure 2 illustrates the results of this artifact removal filtering. NED processing also includes steps to adjust values where adjacent DEM's do not match well and to fill areas of missing data between DEM's. These processing steps ensure that the NED has no void areas and artificial discontinuities have been minimized.

As higher resolution or higher quality data become available, the NED is updated to incorporate the best available coverage. As the USGS's 7.5-minute and 15-minute digital elevation products near completion for the conterminous United States and Alaska respectively, NED data will soon incorporate these sources. For the small areas that are not yet covered, the lower resolution 30-minute and 1-degree USGS DEM products were interpolated to obtain values used in NED. These original elevation files are currently available at http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html. In cases where 7.5-minute DEM's have 10-meter resolution, the original source data will be at a higher resolution than the NED. As more data become available at a finer resolution than that of the NED, the feasibility of developing a finer resolution NED will be investigated.

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Metadata

The Federal Geographic Data Committee's content standard for digital geospatial metadata http://www.fgdc.gov/metadata/contstan.html) will be used to document NED data. Metadata about the individual source datasets used to assemble NED are presented in a spatially referenced form. The polygonal footprint of each part used from a source dataset is retained during NED assembly to provide the spatial context. The attributes of each source dataset, such as original resolution, production method, and date entered into NED, are linked to this polygonal footprint. All of these source polygons together form a national coverage. Through this spatially referenced metadata, the information is made available to the user regarding the source data for any area of NED. For example, a NED user might use the spatially referenced metadata to identify the parts of a study area that were produced by obsolete production methods.

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Applications

Elevation data are an essential part of many earth science applications. They are used for such diverse purposes as providing shaded-relief backgrounds, establishing stratification in land cover classification, doing geometric and radiometric correction of remotely sensed data, indicating landform characteristics such as slope and aspect, and analyzing synthetic drainage networks and watershed delineations through the use of geographic information systems.

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Obtaining Data

Plans are to have NED publicly available by late 2000. The NED will be delivered in the Spatial Data Transfer Standard (SDTS) raster profile. The spatially referenced metadata will be delivered in SDTS topological vector profile. Other formats may also be supported. An Internet browse of NED shaded-relief imagery with vector reference information will be provided as an aid to ordering. A customer can identify the requested area graphically through the Internet browser. That area of interest will be extracted from the NED and from the spatially referenced metadata and formatted for delivery. The data will be available to download from the Internet using file transfer protocol or on standard distribution media. As more information on the NED becomes available, it will be accessible through the Internet at http://gisdata.usgs.gov/ned.

For more information, please contact:
Customer Services
U.S. Geological Survey
EROS Data Center
47914 252nd Street
Sioux Falls, South Dakota 57198-0001
Tel: 800-252-4547
Tel: 605-594-6151
Fax: 605-594-6589
Email: custserv@edcmail.cr.usgs.gov

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Information

For information on these and other USGS products and services, call 1-888-ASK-USGS, use the Ask.USGS fax service, which is available 24 hours a day at 703-648-4888, or visit the general interest publications Web site on mapping, geography, and related topics at http://mapping.usgs.gov/www/products/mappubs.html.

Please visit the USGS home page at http://www.usgs.gov/.

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This document has undergone official review and approval for publications established by the National Mapping Division, U.S. Geological Survey. Some figures have been modified or added to improve the scientific visualization of information.

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U.S. Geological Survey
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URL: *http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs14899.html*
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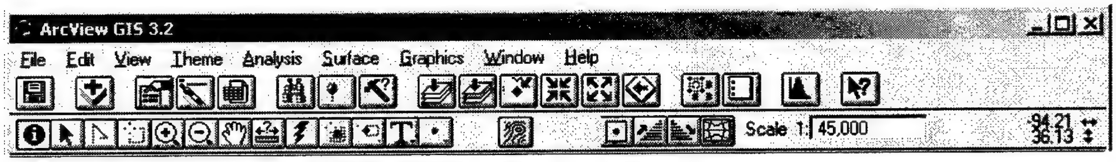
APPENDIX B

Delineation of Areas Affected by Advective Transport in Mantled Karst

Users Manual 1.0 Short

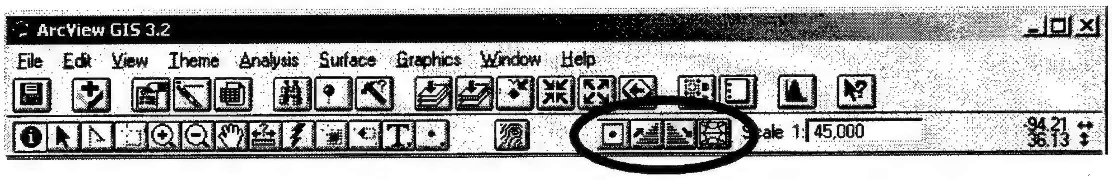
This users manual is intended to be used in conjunction with *AN INTEGRATED RAPID HYDROGEOLOGIC APPROACH TO DELINEATE AREAS AFFECTED BY ADVECTIVE TRANSPORT IN MANTLED KARST, WITH AN APPLICATION TO CLEAR CREEK BASIN, WASHINGTON COUNTY, ARKANSAS* Dissertation (Curtis 2000) using the *Advective Karst Model 1.0* in ArcView 3.2. This manual assumes you are familiar with using ArcView 3.2, ArcView Spatial Analyst, loading extensions, running scripts, and using the map calculator. Extensions needed in conjunction with the project file and DEM preparation are located in the manual's Appendix.



1. Add Grid file Theme to View (normally View 1), remember Grid Data Source
   Grid data must be in integer format, use the map calculator if needed
   All sinks must be filled including one-cell-sinks, use OneCellFill script if needed
2 Add spill location or visual reference
   a. Add GeoTiffs (for location purposes) if spilling by map view, remember Image Data Source
   b. Add text file with spill coordinates, if using GPS coordinates, advanced users
   c. Make theme viewable
3. Add Lineament file Theme to the View and make viewable, remember Feature Data Source
4. Make the Grid theme active by clicking on it in the legend
5. Click spill button
6. Place pointer on the spill location and click the left mouse button
7. Enter distance to find advective flow (keep this as small as possible to shorten run times)
8. Verify if the area of interest is within the circle, if not select "no"
9. Enter file name (for this example "Spill") for the new point shape theme and verify name
10. Make your new working theme "Spill" active and convert it to a shape file
    (for example "runone")
11. Make Lineament theme active
12. Select by Theme under Theme tool
    a. Select spill shape (for this example "Spill")
    b. Select "Area within Distance of"
    c. Place distance, 100 feet, 30 yards or 30 meters
    d. Click new set
    e. Selects lineaments that are near the flow path of the spill
13. Make your working file active (for this example "Spill")
14. Select by Theme under Theme tool
    a. Select Lineament shape
    b. Select "Area within Distance of"
    c. Place distance, 100 feet, 30 yards or 30 meters
    d. Click new set
    e. Selects "Spill" shape points that are near selected lineaments
15. Make the spill theme active (for this example "Spill")
16. Click the Downhill button and then click somewhere in the view
17. Make "Spill" theme active and convert it to a new shape file, example "runtwo"
18. Repeat 11-17 if new lineaments cross the new flow paths and are believed to contribute to the advective transport.

Delineation of Areas Affected by Advective Transport in Mantled Karst
Users Manual 1.0 Long

This users manual is intended to be used in conjunction with *AN INTEGRATED RAPID HYDROGEOLOGIC APPROACH TO DELINEATE AREAS AFFECTED BY ADVECTIVE TRANSPORT IN MANTLED KARST, WITH AN APPLICATION TO CLEAR CREEK BASIN, WASHINGTON COUNTY, ARKANSAS* Dissertation (Curtis 2000) using the *Advective Karst Model 1.0* in ArcView 3.2. This manual assumes you are familiar with using ArcView 3.2, ArcView Spatial Analyst, loading extensions, running scripts, and using the map calculator. Extensions needed in conjunction with the project file and DEM preparation are located in the manual's Appendix. The circled buttons below are the models script buttons used in the project file.

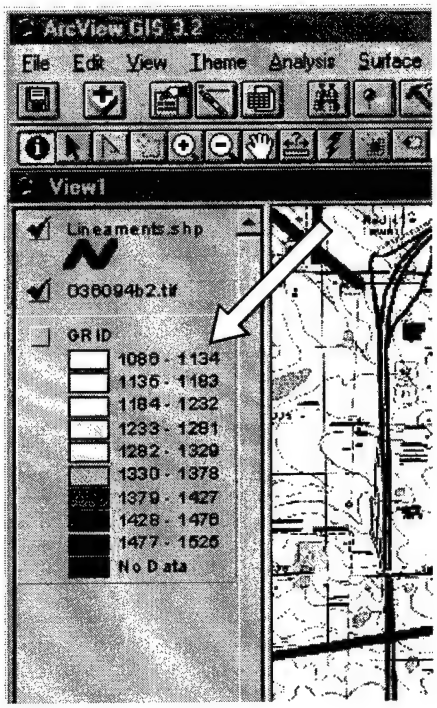


1. Open the project file that contains the model's scripts.
2. Add Grid file Theme to View (normally View 1)
    a. Activate the view you want to add the grid theme to.
    b. Press the Add Theme button. This will bring up the Add Theme dialog.
    c. Change the Data Source Type dropdown list to Grid Data Source in the Add Theme dialog.
    d. Navigate to the directory that contains the grid data source you want to add as a theme.
    e. Select the grid data source and press the OK button in the Add Theme dialog. The grid data source will be added to the active view as a grid theme with a default legend.

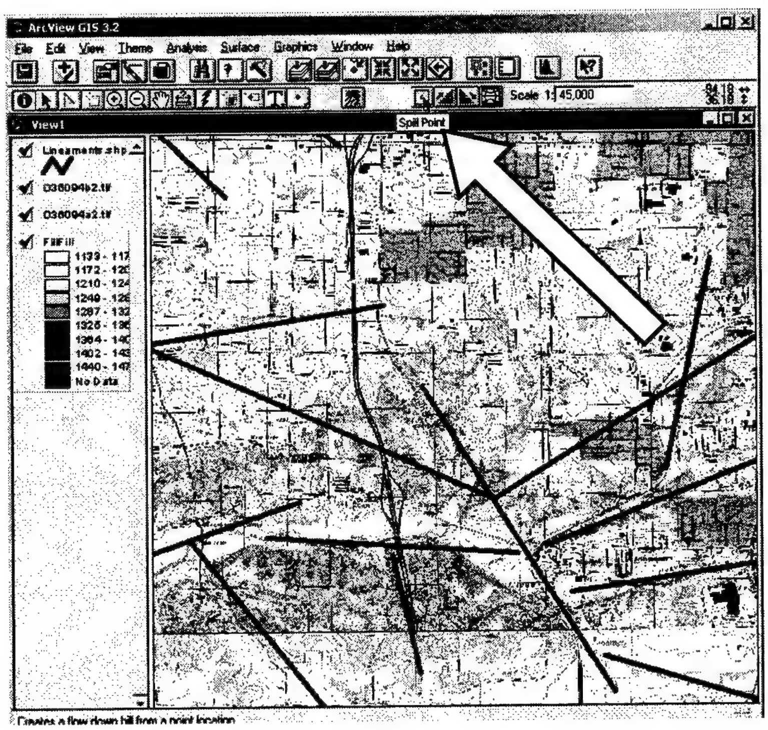
3. Add GeoTiffs (for location purposes) if spilling by map view. Add text file if using coordinates
    a. Activate the view you want to add the GeoTiff theme to.
    b. Press the Add Theme button. This will bring up the Add Theme dialog.
    c. Change the Data Source Type dropdown list to Image Data Source in the Add Theme dialog.
    d. Navigate to the directory that contains the image data source you want to add as a theme.
    e. Select the image data source and press the OK button in the Add Theme dialog. The image data source will be added to the active view as an image theme with a default legend.
    f. Or, add text file with spill coordinates, if using GPS coordinates (Advanced user)
    g. Make theme viewable by checking the box in the legend for that theme.

4. Add Lineament file Theme to the View and make viewable
    a. Activate the view you want to add the shape theme to.
    b. Press the Add Theme button. This will bring up the Add Theme dialog.
    c. Change the Data Source Type dropdown list to Feature Data Source in the Add Theme dialog.
    d. Navigate to the directory that contains the shape data source you want to add as a theme.
    e. Select the shape data source and press the OK button in the Add Theme dialog. The shape data source will be added to the active view as a shape theme with a default legend.
    f. Make theme viewable by checking the box in the legend for that theme.

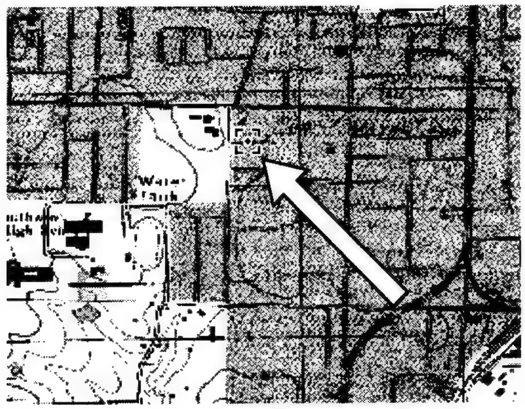
5. Make the Grid theme active by clicking on it in the legend. The theme will highlight to show it is active. In this example, the GRID theme is active but not viewable.



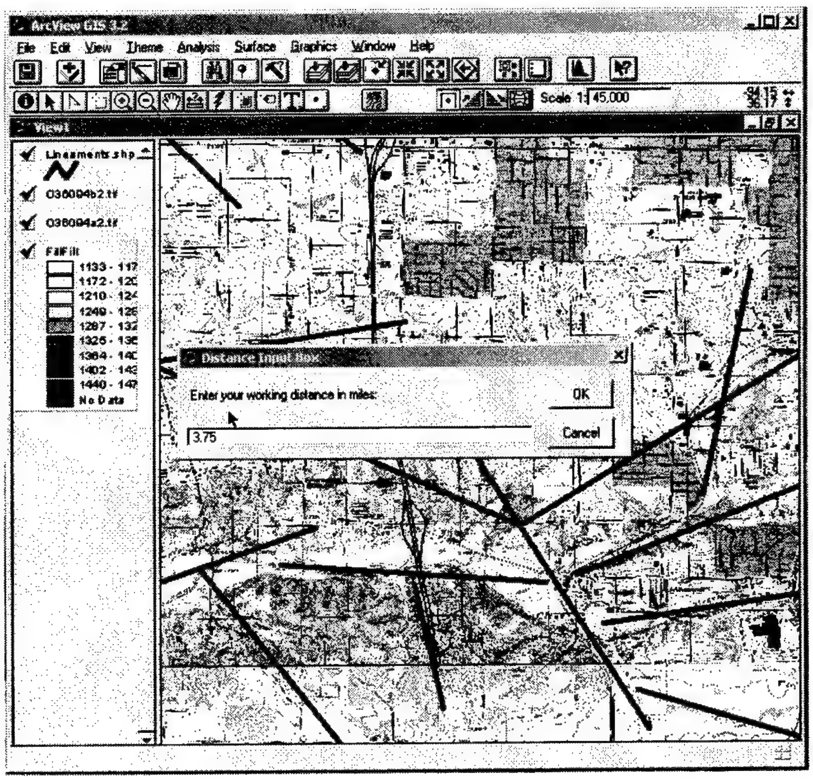
6. Click spill button



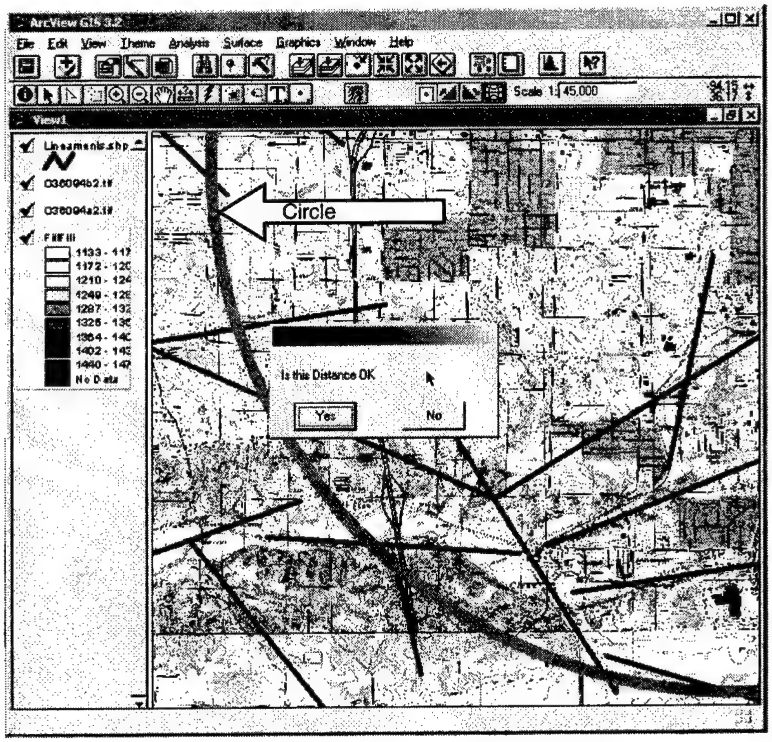
7. Place pointer on spill location and click left mouse button.



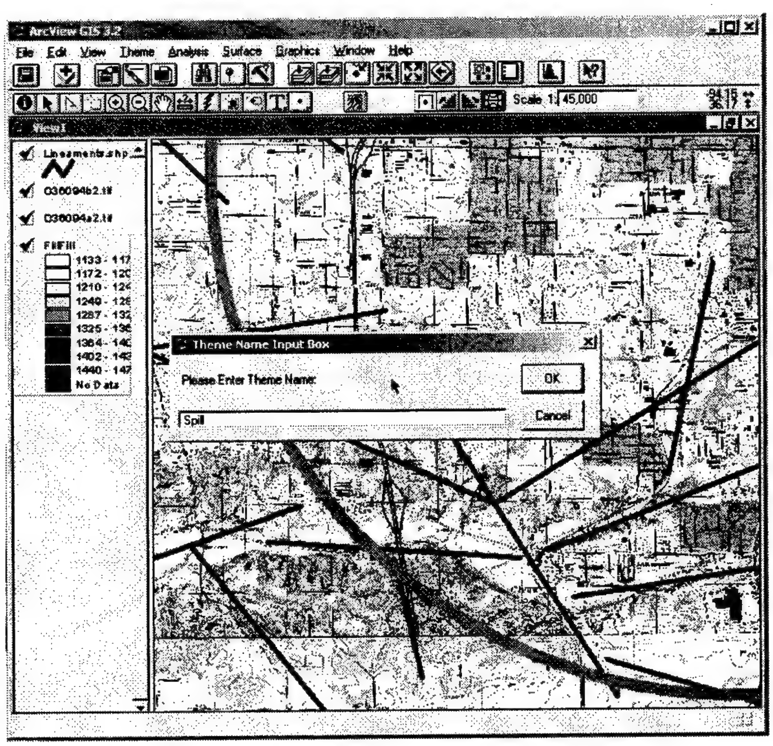
8. Enter the distance in miles to find advective flow (keep this as small as possible to shorten run times). The USGS DEMs are unprojected so distance is only an approximation and should be checked by the next step.



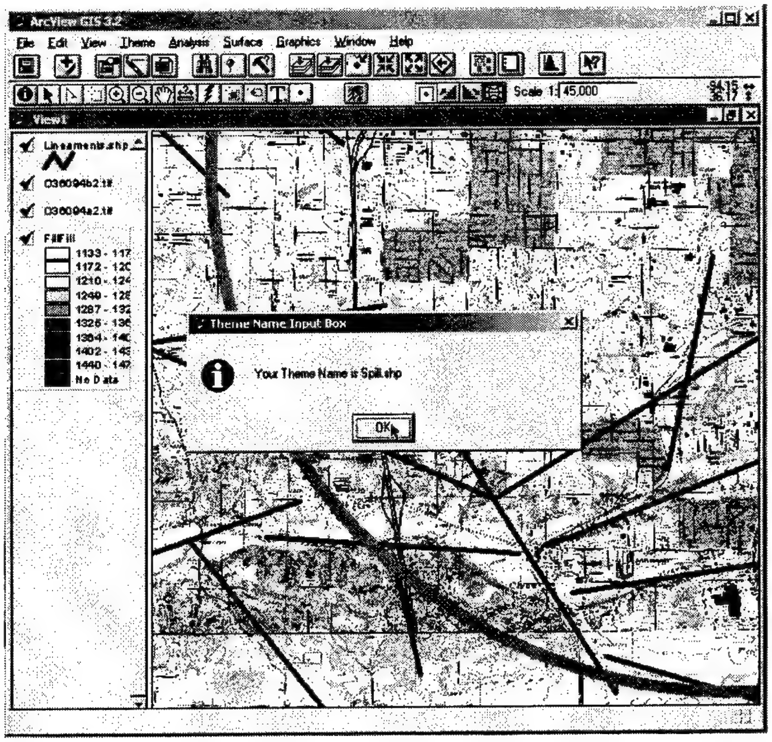
9. Verify if the area of interest is within the circle, if not select "No"



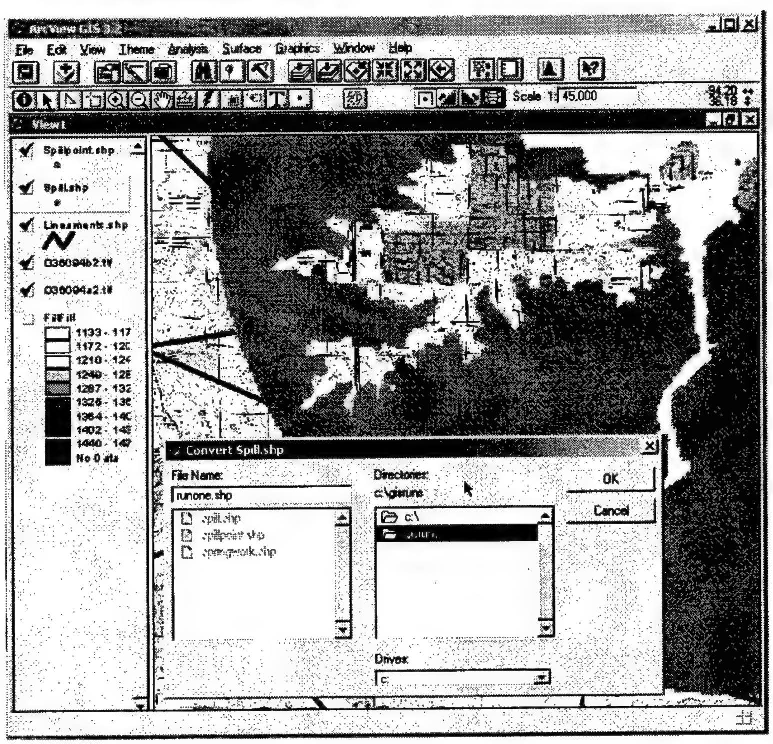
10. Enter file name (for this example "Spill") for new point shape.



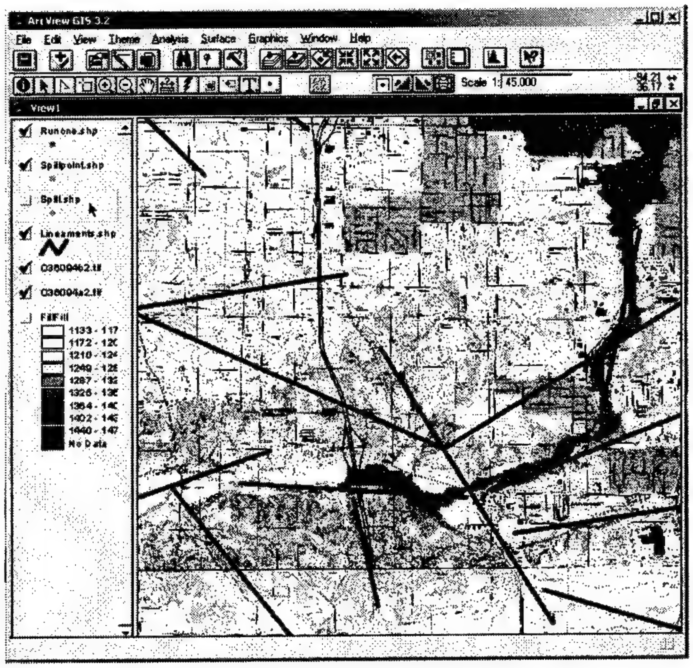
11. Verify name and click OK, the program will start running.



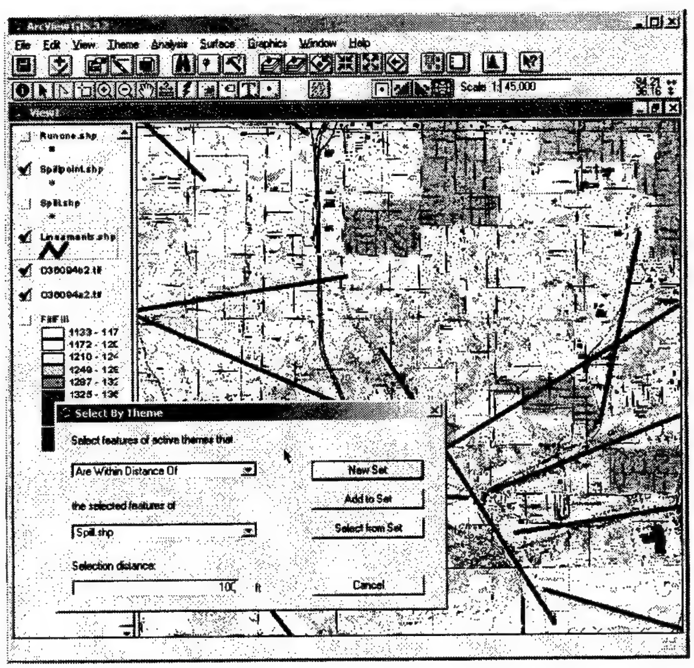
12. Make the new theme "Spill" active and convert selected shape points to a new shape file (for example "runone"), selected shape points will be yellow.



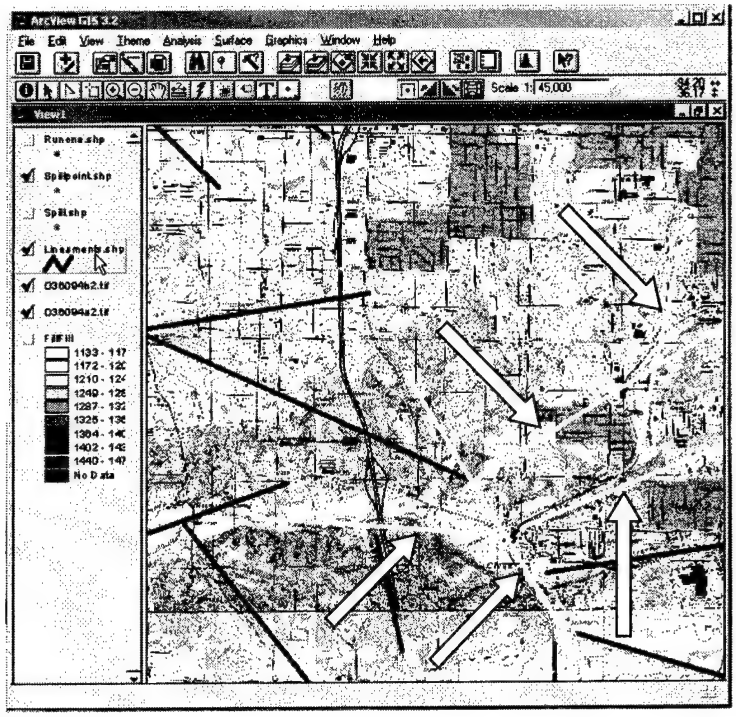
13. After saving the file add the shape file as theme to the view and make viewable if desired.



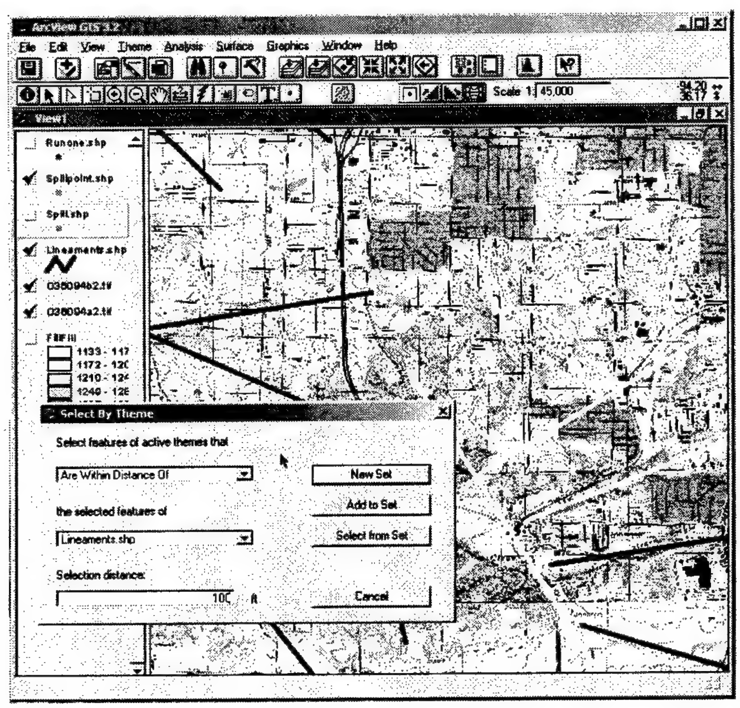
14. Make the Lineament theme active.
15. Select by theme under Theme tool
    a. Select spill shape (for this example "Spill")
    b. Select "Area within Distance of"
    c. Place distance, 100 feet, 30 yards or 30 meters
    d. Click new set
    e. Selects Lineament shapes that are near selected "Spill" shape points.



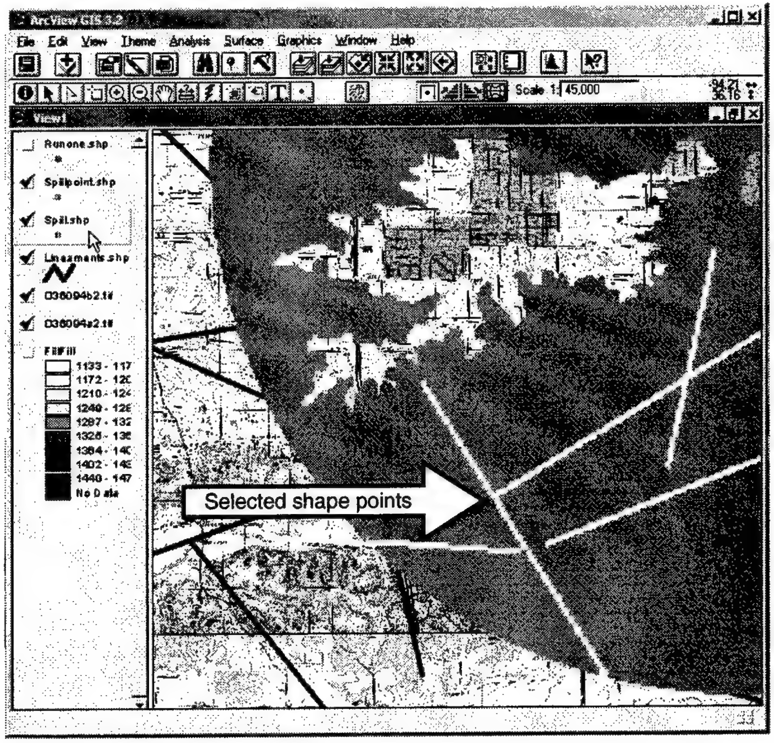
16. Lineaments that intersect the overland flow should be selected (yellow).



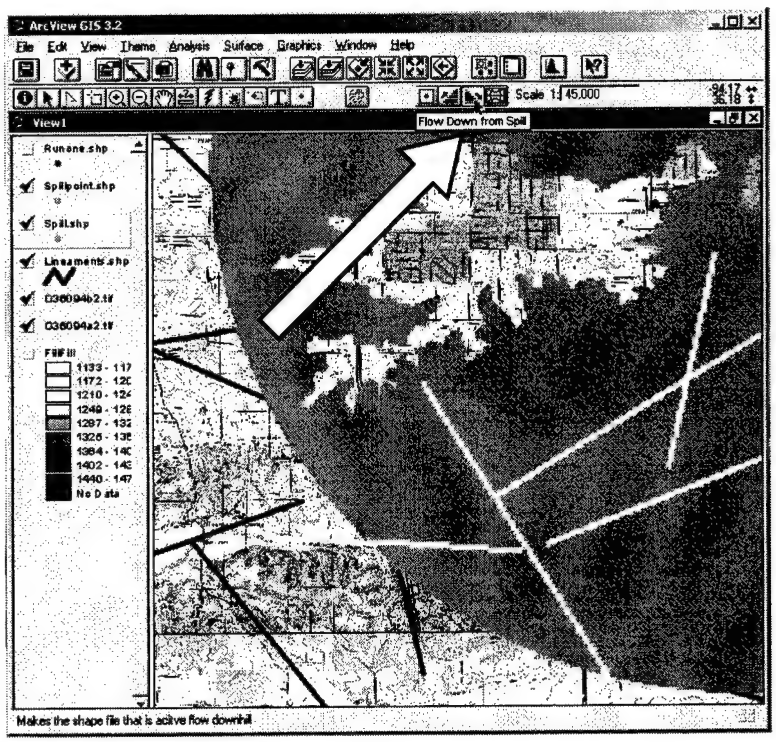
17. Make Spill theme active.
18. Select by theme under Theme tool
    a. Select Lineament shape
    b. Select "Area within Distance of"
    c. Place distance, 100 feet, 30 yards or 30 meters
    d. Click new set
    e. Selects Spill shape points that are near selected lineaments.



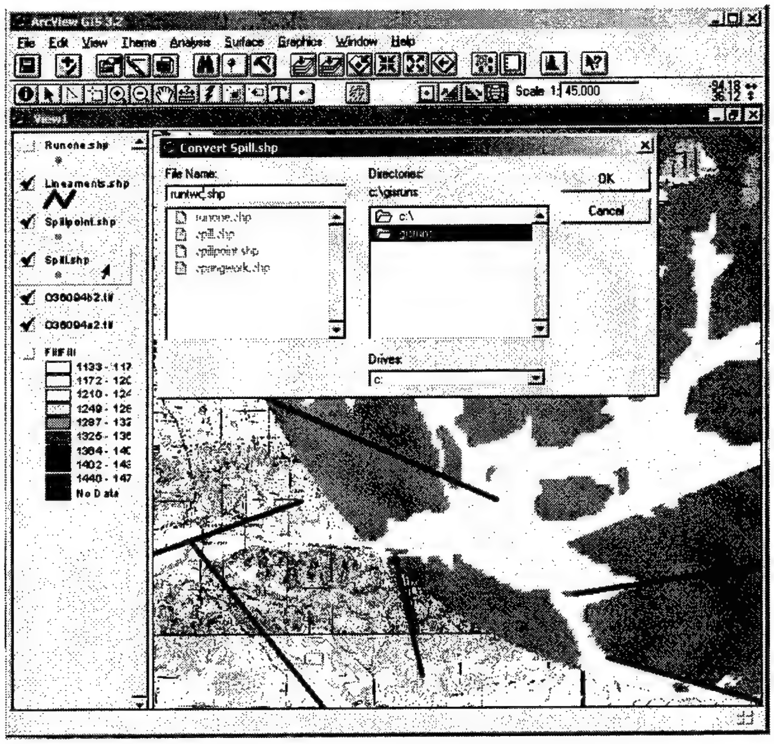
19. The Spill shape data that are within 100 feet of the selected lineaments should be selected (yellow).



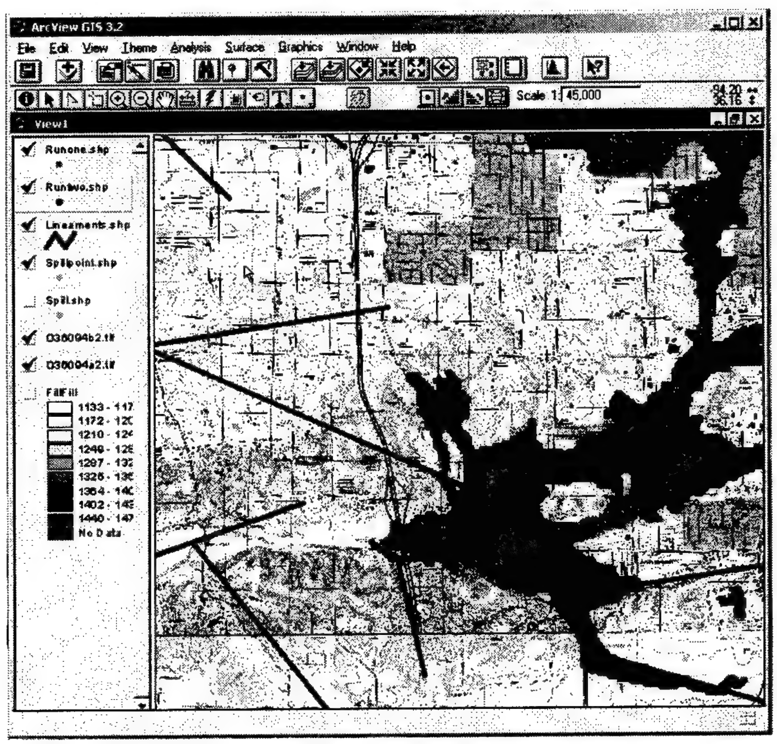
20. Make the Spill theme active.
21. Click the Downhill button and then left click somewhere in the view.



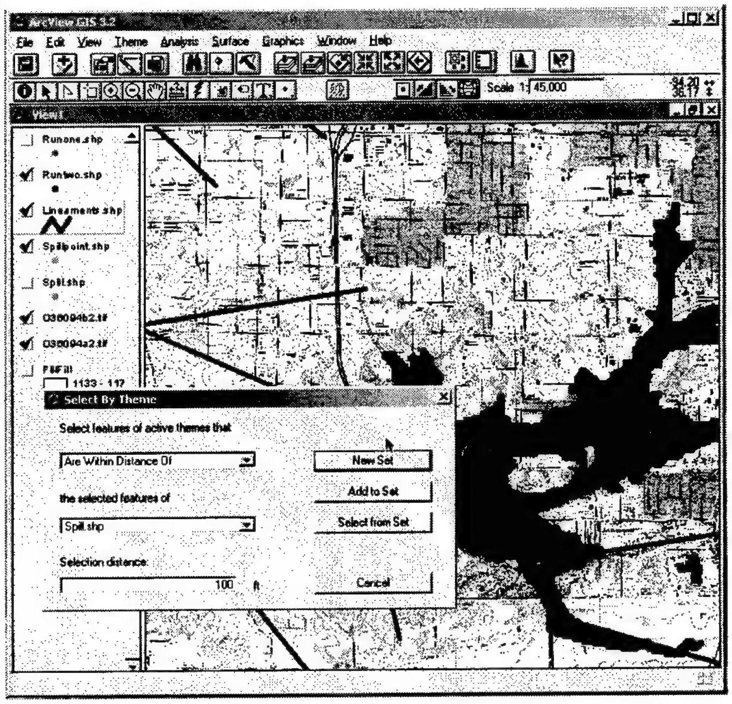
22. Make Spill theme active and convert it to a shape, example "runtwo" and add it to the view.



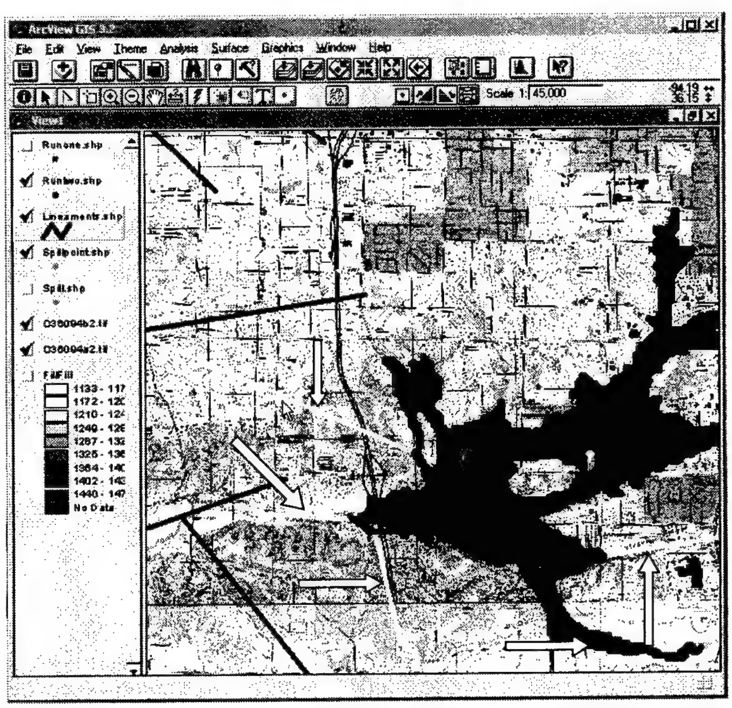
23. Repeat 13-22 if new lineaments cross the new flow paths and may contribute to the advective transport. The spill layers runone and runtwo can now be layered for viewing.



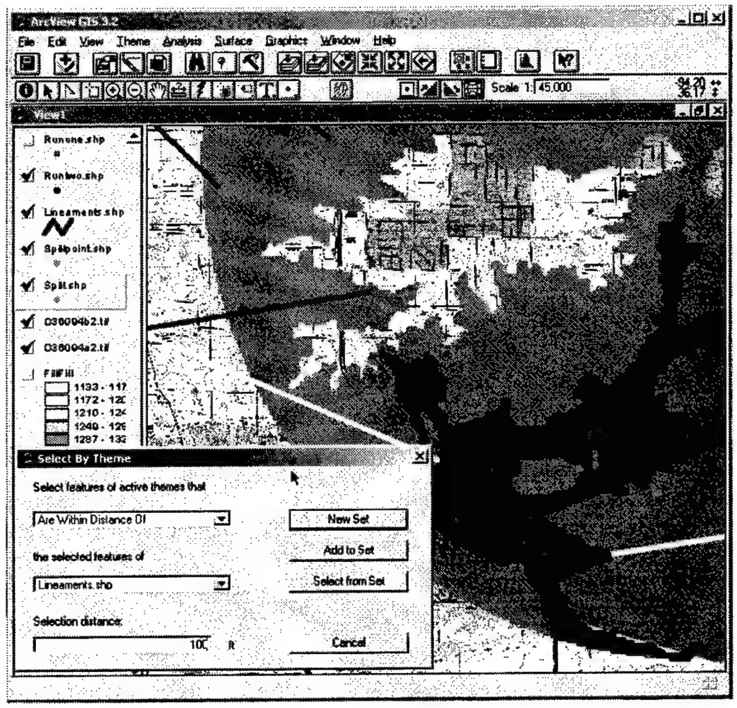
24. Make the Lineament theme active.
25. Select by theme under Theme tool
    a. Select spill shape (for this example "Spill")
    b. Select "Area within Distance of"
    c. Place distance, 100 feet, 30 yards or 30 meters
    d. Click new set
    e. Selects Lineaments that are near selected spill shape points.



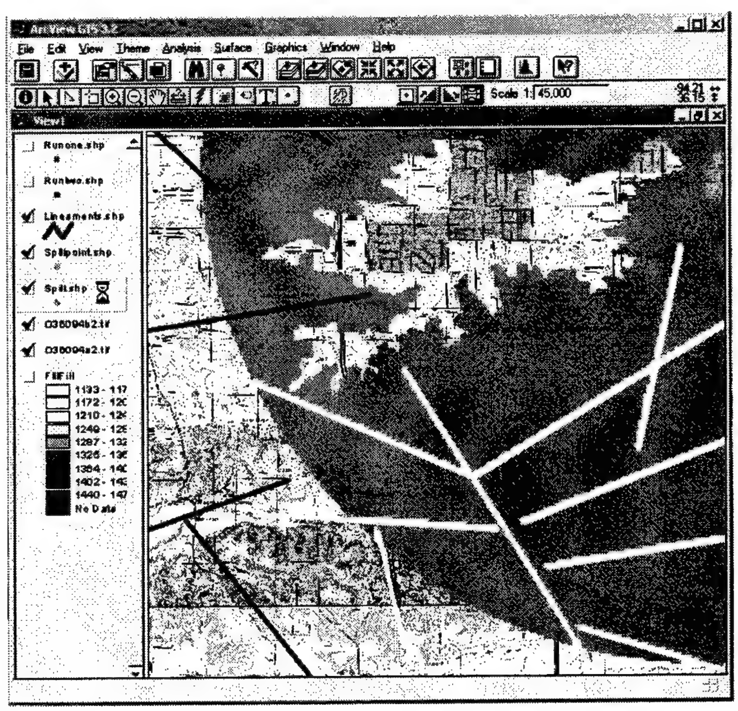
26. The lineaments touching the new overland flow should be selected (yellow).



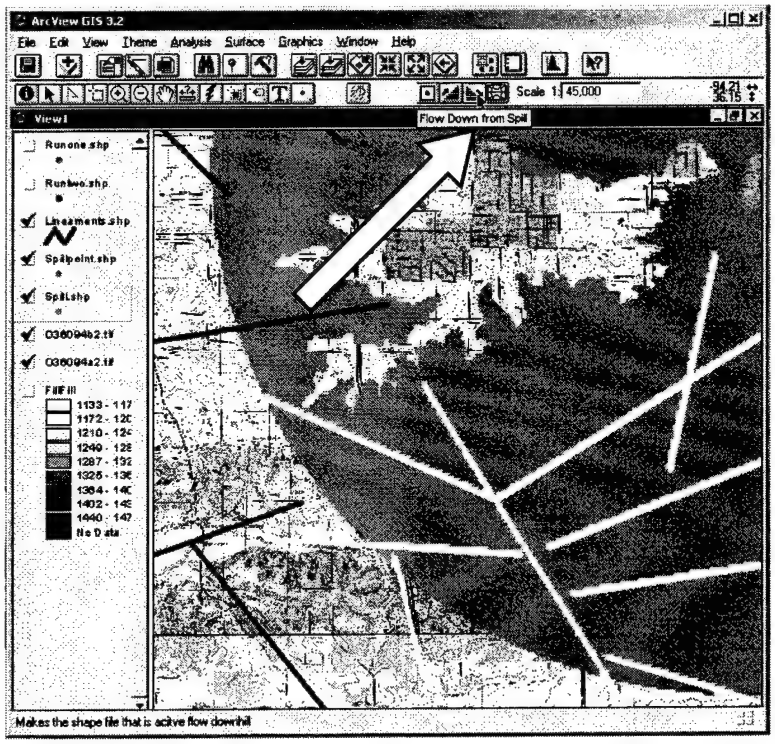
27. Make Spill theme active.
28. Select by theme under Theme tool
    a. Select Lineament shape
    b. Select "Area within Distance of"
    c. Place distance, 100 feet, 30 yards or 30 meters
    d. Click new set
    e. Selects Spill shape points that are near the selected lineaments.



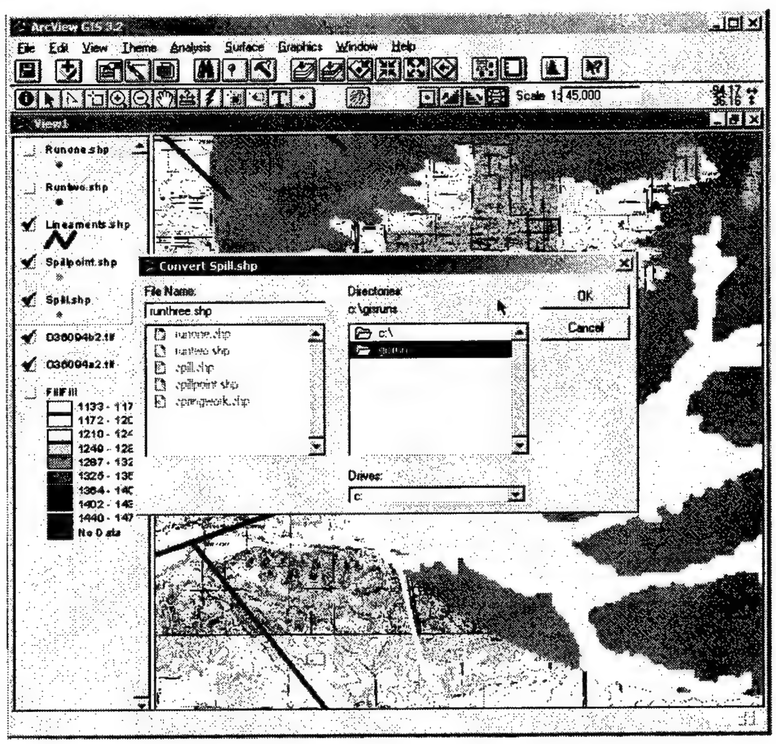
29. The Spill shape data that are within 100 feet of the selected lineaments should be selected (yellow).



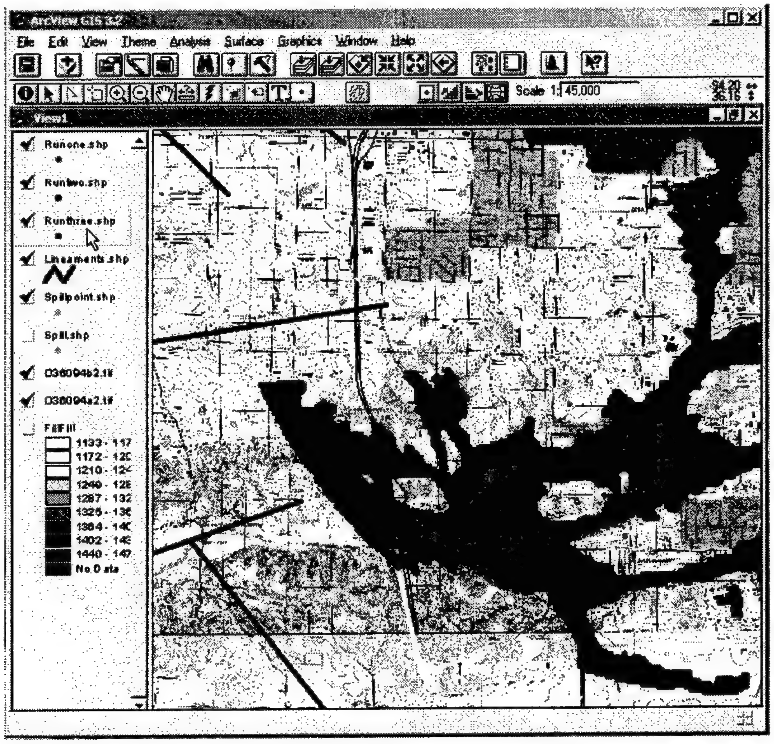
30. Make the Spill theme active.
31. Click the Downhill button and then left click somewhere in the view.



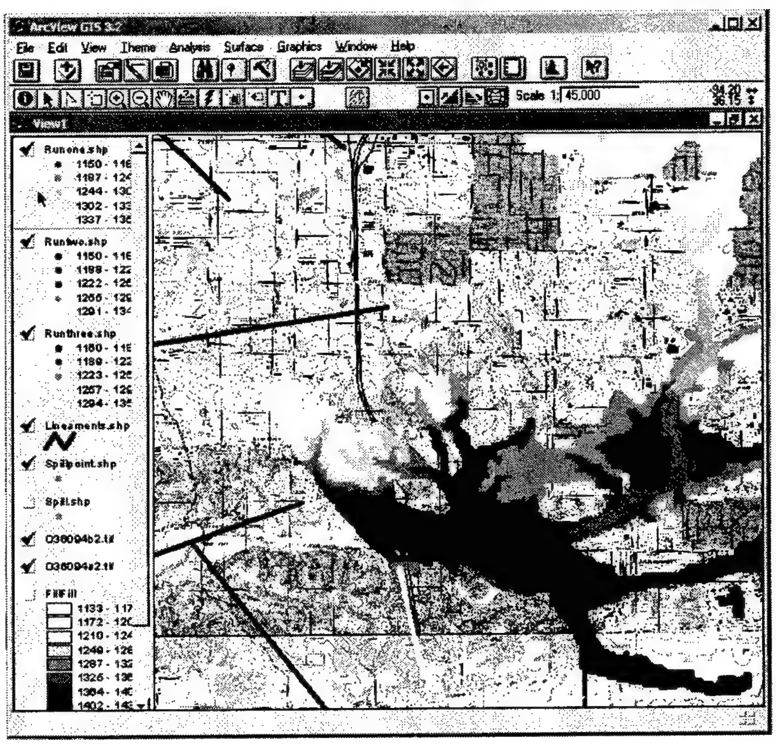
32. Make your Spill theme active and convert it to a shape, example "runthree" and add it to the view.



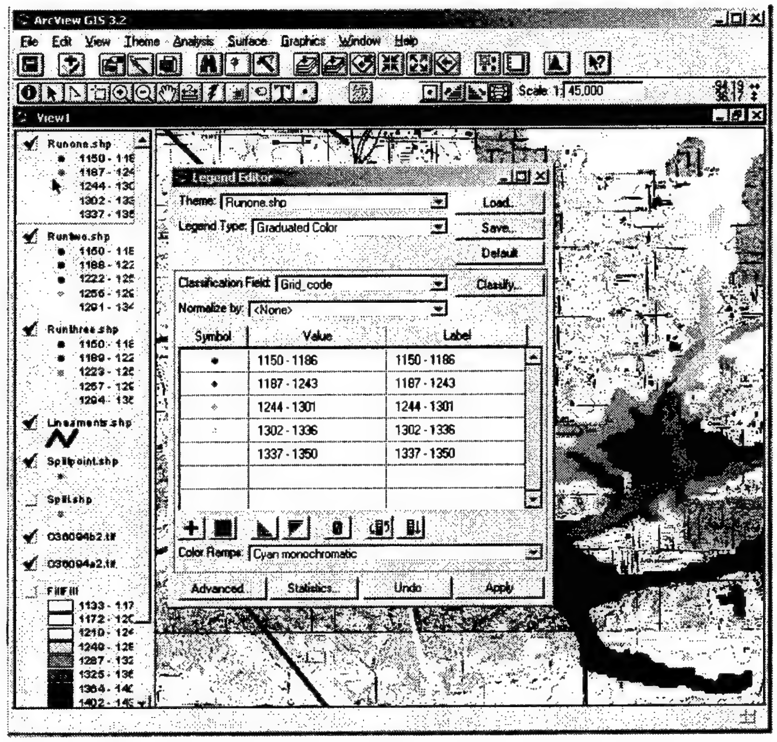
33. Make Runone, Runtwo, and Runthree themes viewable. Uncheck Spill theme to make nonviewable.



34. Change the colors in the legend to suit your needs.



35. By double clicking in the legend the Legend Editor will come up for that theme. For this example the legend type "Graduated Color" was selected along with the "Grid_code" Classification Field.



36. The View can now be printed or saved. In the above example the darker areas indicate lower elevations and should be more prone to spring discharge. The View data can be used as a screening tool for spill point outlets.

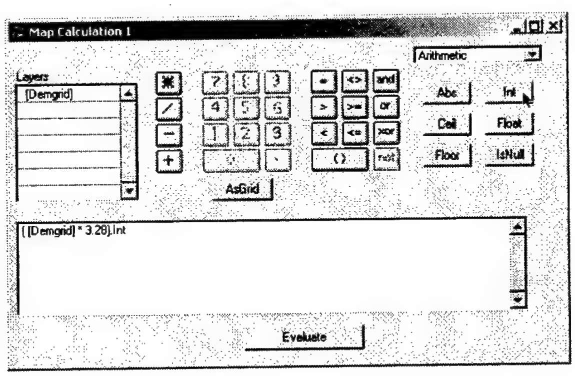
User Manual's Appendix

Delineation of Areas Affected by Advective Transport in Mantled Karst

Users Manual 1.0

The manual is broken up into several parts. The first part is a short explanation of the Spillpoint model run. It may be all that is needed to guide an advanced ArcView user through the model or a novice who has used the model several times. The second part, of the mannal includes longer explanations, including a detailed example of a model run that includes screen shots to guide the user through the first few uses of the model.

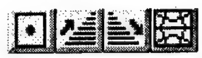
Several things must be completed prior to using the Model. ArcView 3.2 and Spatial Analyst must be loaded on the computer. A lineament shape file and DEM grid file for the area must also be loaded on the computer. The DEM data must be in integer format and have all sinks filled. The screen shot below of the Map Calculator shows how to convert a DEM grid file from meters to feet and change it to an integer.



The DEM can be filled by using the hyro.avx or the hydrov11.avx extensions located in the sample extension file included with ArcView 3.2. For the typical computer setup, they are located in the *C:\ESRI\AV_GIS30\ARCVIEW\Samples\ext* directory. Once the DEM is filled by the ArcView hydro/hydrov11 extension, the one-cell-sinks that remain must be filled. A script OneCellFill is included in the model's project file and can be used to fill any one-cell-sinks that remain. The script may be run by making the Grid Theme (DEM) active, then clicking on the script file and executing the script. Additional information on running scripts can be found in the ArcView help file.

The Buttons

Four new buttons are included with the Project file. They are the **spill**, **uphill**, **downhill** and **make shape from grid** buttons.



The **spill** button  is used to model a spill from one point location and allowing it to flow down hill from that location. The program (script) extracts the area specified by the model user as an input parameter. This area is then extracted from the DEM file and converted to a point shape file that includes the *shape* field, *pointid* field, *grid_code* (DEM elevation) field and two tag fields named *Tag* and *Tag1*. The *Tag* field is used in the initial spill model run. A number is assigned to the *Tag* field if it meets the scripts flow requirements. Any number greater than 0 in the *Tag* field identifies it as being associated with overland flow. The script also excludes any data points having an elevation greater than the initial spill points location.

The **uphill** button  is used for locating springshed boundaries and is used in the same manner as the **downhill** button shown below. The **uphill** button should be used for experimentation purposes at the current time.

The **downhill** button  is used after the **spill** script or the **make shape from grid** script discussed below. The program (script) is used for multi-point spill flow. The **downhill** script is used after the **spill** script run, discussed above, has run and after the selected lineaments have been associated with the spill point shapes. The spill point shapes that are selected act as multi-spill points. The *Tag1* field is used by the **downhill** or **uphill** script if that shape point meets the flow requirements. This field can be used to sort flow points from nonflow points.

The **make shape from grid** button  makes a point shape file from a grid theme and includes the fields discussed earlier in the **spill** button paragraph. This script is used when the user wants to start with a multi-point flow. Before using the **make shape from grid** button, the grid theme can be trimmed to exclude areas that may not be needed and thus reduce the run time of

the **downhill** or **uphill** script. A very nice extension is located on the ESRI site (http://gis.esri.com/arcscripts/beginsearch.cfm). This will cut the Grid Theme into a smaller working file. The extension's name is *Grid Analyst Extension*.

APPENDIX C

```
'Spill Point

'this script must be used from an apply event
'click anywhere on the tool bar (not on a button)
'from the view-tool make a button and apply this script
'this is explained in the users manual

'gets the active view and makes the grid theme you have active
'theGridTheme

theView = av.GetActiveDoc
theDisplay = theView.GetDisplay
theGridTheme = theView.GetActiveThemes.Get(0)
theGrid = theGridTheme.GetGrid
'Returns the users point and gets the cells value
thePoint = theDisplay.ReturnUserPoint
elevatpoint = theGrid.CellValue(thePoint,Prj.MakeNull)


'This selects the distance to work with as a user input
'It displays a circle of the approximate distance
'if the circle does not reach the user expected point
'say no and it will let you start the program over
t="Distance Input Box"
ch = MsgBox.Input("Enter your working distance in miles:",t,"1")
begindist=ch.AsNumber
 if (ch=nil) then
  MsgBox.Warning("Cancel Pressed: No Data Entered","Canceling the Dialog")
 exit
 else
  Dist = Units.Convert (begindist,#UNITS_LINEAR_MILES, av.GetActiveDoc.GetDisplay.GetU-
nits)
  mystartCircle=Circle.Make(thePoint,dist)
  thesym=Symbol.Make(#SYMBOL_PEN)
  thesym.setwidth(9)
  theDisplay.BeginClip
  theDisplay.DrawCircle(mystartCircle,theSym)
  theDisplay.EndClip
  goornot=MsgBox.MiniYesNo("Is this Distance OK",true)
   if (goornot=false) then
   thestring1="try it again"
   MsgBox.info("Try Again",thestring1)
   exit
   end
 end
'End of collecting the user distance for the program

'Selects the Grid and cuts it to size before doing any calcs
cutgrid=theGrid.ExtractByCircle(mystartCircle,Prj.MakeNull,False)
theGrid=cutgrid

'makes a grid that only includes cells below the elevation
'of the user point
Belowgrid=(theGrid/theGrid)*elevatpoint
```

```
usergrid=theGrid<=Belowgrid
usergrid1=Belowgrid/usergrid
usergrid2=(usergrid1/usergrid1)*theGrid

'makes a grid for the users point
mPoint = MultiPoint.Make({thePoint})
theSrcGrid = theGrid.ExtractByPoints(mPoint,Prj.MakeNull,FALSE)


'gets a distance, makes a circle and extracts grid cells that fall within the
'distance   *the end grid includes cells below the user point and within a distance
'this was done to reduce the amount of records to process
myCircle=Circle.Make(thePoint,Dist)
usergrid4=usergrid2.ExtractByCircle(myCircle,Prj.MakeNull,False)


'changes the grid below user point elevation/within distance to point shape file
'Name1="Working.shp".AsFileName

' Variable Initialization Naming
t="Theme Name Input Box"
' Loop forever.
while (true)
 ch=MsgBox.Input("Please Enter Theme Name:",t,"SpringWork")
 if (ch = nil) then
   MsgBox.Warning("Cancel Pressed: No Data Entered", "Canceling the Dialog")
   Exit
 else
 name=ch+".shp"
 name1=name.AsFileName
     MsgBox.Info("Your Theme Name is" ++ name, t)
 end
 'End of naming



myFTab=usergrid4.AsPointFTab(Name1,Prj.MakeNull)
'theView.AddTheme(FTheme.Make(myFTab))

'changes the user point grid to point shape file (has one record)
h="SpillPoint.shp".AsFileName
ShapePoint=theSrcGrid.AsPointFTab(h,Prj.MakeNull)
myFTabpoint=FTheme.Make(ShapePoint)
'theView.AddTheme(myFTabpoint)


xfld = field.make("Tag",#FIELD_DOUBLE, 9, 2)
xfld1 = field.make("Tag1",#FIELD_DOUBLE, 9, 2)

myFTab.setEditable(true)
myFTab.addfields({xfld,xfld1})

'Getting fields
```

```
Taged=myFTab.FindField("Tag")
fieldshape=shapepoint.FindField("shape")
fieldshape1=myFTab.FindField("shape")

'finding spill point and tagging myFTab shape file with 1 under "Tag"
'makes aBitmap for myFTab and sets selection for Tag=1, the spill point
for each ii in shapepoint
 shapelocation=shapepoint.ReturnValue(fieldshape, ii)
  for each i in myFTab
   newshape=myFTab.ReturnValue(fieldshape1,i)
    if (newshape=shapelocation) then
    myFTab.SetValue(Taged,i,1)
    theSelSize=myFTab.GetNumRecords
    Yellow=Bitmap.Make(theSelSize)
    Yellow.SetAll
    expr="([Tag] = 1)"
    myFTab.Query(expr,Yellow,#VTAB_SELTYPE_NEW)
    myFTab.SetSelection (Yellow)
    end
 end
end
'myFTab.setEditable(false)
theFTheme=FTheme.Make(myFTab)
'theFTheme.SetVisible(True)
theView.AddTheme(theFTheme)
myFTab.Refresh

'*********************************************************************************

'The start of the flow

theGridTheme.SetActive(False)
theFTheme.SetActive(True)
theView = av.GetActiveDoc
theTheme = theView.GetActiveThemes.Get(0)
theFTab = theTheme.GetFTab
theDpy = theView.GetDisplay
theFTheme.SetVisible(True)


dis50m = Units.Convert(50, #UNITS_LINEAR_METERS, theDpy.GetUnits)
dis2m = Units.Convert(2, #UNITS_LINEAR_METERS, theDpy.GetUnits)

shapeField = theFTab.FindField("Shape")
gridField = theFTab.FindField("Grid_code")
tagField = theFTab.FindField("tag")

theFTab.SetEditable(TRUE)

Big=((begindist*1609)/30)
'Added more loops for non straight line runs
Big=(Big+25)

for each round in 1..(Big-1)
 theBitMap = theFTab.GetSelection
```

```
qstring = "([tag] = "+round.AsString+")"
theFtab.Query(qstring, theBitMap, #VTAB_SELTYPE_NEW)

for each rec in theBitMap

  theFromPoint = theFTab.ReturnValue(shapeField, rec)
  theFromGridValue = theFTab.ReturnValue(gridField, rec)
  theFTab.SelectByPoint(theFromPoint, dis50m,#VTAB_SELTYPE_NEW)
  theFTab.SelectByPoint(theFRomPoint, dis2m, #VTAB_SELTYPE_XOR)
  theNewBitMap = theFTab.GetSelection

  for each rec2 in theNewBitMap

    theToGridValue = theFTab.ReturnValue(gridField, rec2)
    theTagValue = theFTab.ReturnValue(tagField, rec2)

    if ((theToGridValue <= theFromGridValue) and (theTagValue = 0)) then

      theFTab.SetValue(tagField,rec2,round+1)

    end

  end

end

end

theFTab.SetEditable(FALSE)


theBitMap.SetAll
expr="([Tag] > 0)"
theFTab.Query(expr,theBitMap,#VTAB_SELTYPE_NEW)
theFTab.SetSelection (TheBitMap)
theView.AddTheme(myFTabpoint)

myFTabpoint.SetVisible(True)
theFTheme.SetVisible(True)
theFTab.Refresh

exit
end
```

APPENDIX D

```
'Flowdown

theView = av.GetActiveDoc
theTheme = theView.GetActiveThemes.Get(0)
theFTab = theTheme.GetFTab
theDpy = theView.GetDisplay

dis50m = Units.Convert(50, #UNITS_LINEAR_METERS, theDpy.GetUnits)
dis2m = Units.Convert(2, #UNITS_LINEAR_METERS, theDpy.GetUnits)

shapeField = theFTab.FindField("Shape")
gridField = theFTab.FindField("Grid_code")
tagField = theFTab.FindField("tag")
tag1Field =theFTab.FindField("tag1")

theFTab.SetEditable(TRUE)

for each record in theFTab.GetSelection
theFTab.SetValue(tag1Field, record, 1)
end


for each round in 1..100
 theBitMap = theFTab.GetSelection
 qstring = "([tag1] = "+round.AsString+")"
 theFtab.Query(qstring, theBitMap, #VTAB_SELTYPE_NEW)

 for each rec in theBitMap

  theFromPoint = theFTab.ReturnValue(shapeField, rec)
  theFromGridValue = theFTab.ReturnValue(gridField, rec)
  theFTab.SelectByPoint(theFromPoint, dis50m,#VTAB_SELTYPE_NEW)
  theFTab.SelectByPoint(theFRomPoint, dis2m, #VTAB_SELTYPE_XOR)
  theNewBitMap = theFTab.GetSelection

  for each rec2 in theNewBitMap

   theToGridValue = theFTab.ReturnValue(gridField, rec2)
   theTagValue = theFTab.ReturnValue(tag1Field, rec2)

   if ((theToGridValue <= theFromGridValue) and (theTagValue = 0)) then

    theFTab.SetValue(tag1Field,rec2,round+1)

   end

  end

 end

end

TheFTab.SetEditable(FALSE)
```

```
theBitMap.SetAll
expr="([Tag1] > 0)"
theFTab.Query(expr,theBitMap,#VTAB_SELTYPE_NEW)
theFTab.SetSelection (TheBitMap)

'theFTheme=FTheme.Make(theFTab)
'theView.AddTheme(theFTheme)
```

APPENDIX E

```
'OneCellFill

'This Script gets the Active GTheme (DEM) and fills in all sinks that are
'one cell by one cell in size
'You must first fill the sinks by using Fill under the Hydro Sample Extension
'The sample extension does not fill one X one sinks

theView = av.GetActiveDoc
theDisplay = theView.GetDisplay
theGridTheme = theView.GetActiveThemes.Get(0)
theGrid = theGridTheme.GetGrid
theVTab = theGrid.GetVTab
theSelSize=theVTab.GetNumRecords
theBitMap=Bitmap.Make(theSelSize)
aQueryString="([Value] = 1)"

x=1
while (x>0)

 newGrid=theGrid.FocalFlow(Nil)
 newGrid255=(newGrid=255)
 newVTab=newGrid255.GetVTab
 newVTab.Query(AQueryString,theBitmap,#VTAB_SELTYPE_NEW)
 x=theBitmap.Count
 theGrid=theGrid+newGrid255

end

t111=GTheme.Make(theGrid)
theView.AddTheme(t111)
```

APPENDIX F

```
'Flowup

theView = av.GetActiveDoc
theTheme = theView.GetActiveThemes.Get(0)
theFTab = theTheme.GetFTab
theDpy = theView.GetDisplay

dis50m = Units.Convert(50, #UNITS_LINEAR_METERS, theDpy.GetUnits)
dis2m = Units.Convert(2, #UNITS_LINEAR_METERS, theDpy.GetUnits)

shapeField = theFTab.FindField("Shape")
gridField = theFTab.FindField("Grid_code")
tagField = theFTab.FindField("tag")
tag1Field =theFTab.FindField("tag1")

theFTab.SetEditable(TRUE)

for each record in theFTab.GetSelection
theFTab.SetValue(tag1Field, record, 1)
end


for each round in 1..100
 theBitMap = theFTab.GetSelection
 qstring = "([tag1] = "+round.AsString+")"
 theFtab.Query(qstring, theBitMap, #VTAB_SELTYPE_NEW)

 for each rec in theBitMap

  theFromPoint = theFTab.ReturnValue(shapeField, rec)
  theFromGridValue = theFTab.ReturnValue(gridField, rec)
  theFTab.SelectByPoint(theFromPoint, dis50m,#VTAB_SELTYPE_NEW)
  theFTab.SelectByPoint(theFRomPoint, dis2m, #VTAB_SELTYPE_XOR)
  theNewBitMap = theFTab.GetSelection

  for each rec2 in theNewBitMap

   theToGridValue = theFTab.ReturnValue(gridField, rec2)
   theTagValue = theFTab.ReturnValue(tag1Field, rec2)

   if ((theToGridValue >= theFromGridValue) and (theTagValue = 0)) then

    theFTab.SetValue(tag1Field,rec2,round+1)

   end

  end

 end

end

TheFTab.SetEditable(FALSE)
```

```
theBitMap.SetAll
expr="([Tag1] > 0)"
theFTab.Query(expr,theBitMap,#VTAB_SELTYPE_NEW)
theFTab.SetSelection (TheBitMap)

'theFTheme=FTheme.Make(theFTab)
'theView.AddTheme(theFTheme)
```

APPENDIX G

```
'Make shape from grid

theView = av.GetActiveDoc
theDisplay = theView.GetDisplay
theGridTheme = theView.GetActiveThemes.Get(0)
theGrid1 = theGridTheme.GetGrid



'changes the grid below user point elevation/within distance to point shape file

' Variable Initialization Naming
t="Theme Name Input Box"
' Loop forever.
while (true)
 ch=MsgBox.Input("Please Enter Theme Name:",t,"SpringWork")
 if (ch = nil) then
  MsgBox.Warning("Cancel Pressed: No Data Entered", "Canceling the Dialog")
  Exit
 else
 name=ch+".shp"
 name1=name.AsFileName
   MsgBox.Info("Your Theme Name is" ++ name, t)
 end
 'End of naming

myFTab=theGrid1.AsPointFTab(Name1,Prj.MakeNull)
xfld = field.make("Tag",#FIELD_DOUBLE, 9, 2)
xfld1 = field.make("Tag1",#FIELD_DOUBLE, 9, 2)

myFTab.setEditable(true)
myFTab.addfields({xfld,xfld1})

theView.AddTheme(FTheme.Make(myFTab))

 exit
end
```

AN INTEGRATED RAPID HYDROGEOLOGIC APPROACH TO DELINEATE AREAS AFFECTED BY ADVECTIVE TRANSPORT IN MANTLED KARST, WITH AN APPLICATION TO CLEAR CREEK BASIN, WASHINGTON COUNTY, ARKANSAS

Abstract dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

By

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University of Arkansas, 1988
University of Arkansas, 1989

August 2000
University of Arkansas

ABSTRACT

AN INTEGRATED RAPID HYDROGEOLOGIC APPROACH TO DELINEATE AREAS AFFECTED BY ADVECTIVE TRANSPORT IN MANTLED KARST, WITH AN APPLICATION TO CLEAR CREEK BASIN, WASHINGTON COUNTY, ARKANSAS

by

Darrin L. Curtis

This study focuses on the development of a model for rapid, cost-effective, qualitative predictions of advective transport in areas similar to that found in the fractured mantled-karst of Northwest Arkansas. The model was designed using ArcView Geographic Information System (GIS) software to predict potential advective transport routes at site-specific scale. Although ArcView software was used, the methodology of the model may be rewritten into other GIS languages, if so desired. The model uses topography and a fracture geology coverage layer (lineaments) to visually represent areas affected by flow along preferential pathways.

The methodology of the model was designed to be used with minimal data input. ArcView GIS software, scripts (user written programs within ArcView), Digital Elevation Models (DEM), and lineament data are all that is needed to run the model. The results of the model are qualitative and should only be used with the understanding that they represent the most likely travel routes associated with data being used for that particular model run.

The model was successfully tested and showed advective transport flow patterns that mirrored actual case studies. The tests confirming the models ability to predict advective transport were run in and near Clear Creek Basin in Washington County, Arkansas.

Application of the model greatly enhances our ability to predict interbasin transport, common in karst areas. For example, if a spill occurs, the model will predict likely potential interbasin transfers that DEM's alone would not show. Therefore, water supplies that have the potential to be impacted (impaired) by a contaminant can be monitored, and response scenarios including treatment or discontinuation of use can be evaluated and implemented before damage occurs. Other potential uses of the model include prevention of adverse health effects, avoidance of ruined PVC piping in water distribution systems, and minimization of livestock loss, fish kills, and stream impairment.

Potential users of the model have also expressed an interest in using the model's methodology for springhead protection. Therefore, additional scripts were written to accomplish springshed delineation for use in determining potential areas of spring source water.

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